Antimatter Containment Unit FR

Date: 04/23/2020

Project Description:	Design and implementation of antimatter containment unit
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1 Executive Summary

In 1928, physicist Paul Dirac published a paper that turned the world of physics as we had known it on it's head. Dirac had proposed an alternate version of the famous Schrödinger wave equation that hinted at the existence of a new type of fundamental particle; one that mirrored the electron, but with a positive charge. This discovery opened the physics world up to the concept of antimatter. For all intents and purposes, this new antimatter mimics regular matter very closely; however, the charge of the component subatomic particles is reversed. Perhaps more interestingly though, is the vehement interaction between matter and antimatter, which causes the mutual annihilation of both parties.

It is now 2020, nearly 100 years after the first discovery of antimatter, and still, there have only been marginal discoveries within the field. To change this, the antimatter containment unit has been developed to make the field of antimatter more accessible to upcoming physicists. The main deliverable of this project is to set up a physics laboratory for final year physics students at York University. This laboratory will have the students conduct the same antimatter containment experiment that has been designed by the project team outlined in this document. This allows us to achieve a huge milestone for studying antimatter in Canada as this will be the first time that students will be able to learn about antimatter from a hands on perspective at the undergraduate level.

Aside from this unique opportunity of setting up Canada's first undergraduate antimatter laboratory, this project has many other use cases. One such use of the positrons collected in the experiment is in positron emission tomography (PET) scans, which is a type of medical technique that allows doctors to diagnose various diseases such as dementia or lung cancer. A more novel use case for positron emissions is in material science for detecting impurities in materials. Since positrons flow through a material along the path of least resistance, they can easily detect impurities in crystals since an impurity in a crystal structure would cause an annihilation that can be recorded. These are indeed interesting use cases, and more will certainly be discovered as more research and learning opportunities open up in the field of antimatter.

From setting a country wide milestone, to opening the industry up to more use cases of this fascinating substance; it is clear that there are many benefits, but perhaps the biggest benefit is to the future physics students that will be graduating from York University. Having an opportunity to learn about a field of physics that is renowned as a very complex and is usually a graduate level topic so early will be very valuable for these students. Perhaps what they will learn in this lab will influence their further research, and the antimatter containment unit could be expanded to contain and do research on other types of antimatter particles, such as anti protons. By facilitating these learning opportunities, we are directly accelerating the pace of learning in the field of antimatter, allowing us to discover more about what it is that we are all made of, and why we are here in this universe.

2 Requirements Review

The tables in append A outline the requirements as they were set in the PDR, with a few changes to better justify the need for a few requirements, and updates to the verification/validation process that occured throughout the project. The tables are broken into three sections to indicate the progress towards achievement of the requirement; unfortunately due to the Covid-19 pandemic, not all requirements could be fulfilled. Note that the tables in appendix A also outline the verification and validation status for the completed requirements, or the intended way to verify and validate the requirement for the incomplete ones.The original unchanged document from the PDR can be accessed through the following link.

https://drive.google.com/file/d/1XgtguaEPqdF96Gjzr4jCogYAPbQ_2hGR/view?usp=sharing

2.1 Key Requirements

The requirements listed in appendix A were designed to help the project team implement a solution to meet the needs of the project stakeholders. Specifically, these requirements tackle the problem of producing and containing antimatter in a safe way that can be easily replicated by students at an undergraduate level, thus improving their education. The secondary problem that these requirements were designed for is determining a way of developing the experiment as cost effectively as possible to find better ways to give the industry positrons technology, for instance, in PET scanning equipment or material impurity detection devices. To meet these needs, a few requirements are more vital than others; these key requirements are listed as follows.

P-FUN-50 - Instrument Assembly for Positron Trapping

This requirement essentially captures the goal of the project, that is, to contain positrons. This requirement aids in the stakeholder need of setting up a laboratory for 4th year physics students. The design, and successful implementation of this component will act as a proof of concept that can be easily replicated by future physics students, provided that they have the necessary documentation (this will also be developed by the project team). This requirement also aids in meeting the secondary needs of providing various industries with other means of acquiring positrons. The trapping section of the experiment is what allows positrons to be contained. Once contained, can be collected for a short duration before being released all at once. This release can be useful in medical devices such as PET scans which can diagnose brain diseases like dementia, or other diseases such as types of cancer.

This requirement involves constructing the designed trapping section of the design, and is the last step in the assembly process before verification testing can begin. Since this requirement is one that is so closely tied to the goal of the project, it is also one of the last ones in the project timeline to be met. Unfortunately, at this time, this requirement remains unmet due to the Covid-19 pandemic; however, much of the project team is eager to continue this project. It is expected that this requirement will be met within three weeks once the project team is able to meet to begin working again.

P-INT-40 - Turbomolecular Pump Emergency Stop Mechanism

This requirement is not a key requirement because it directly relates to a deliverable for the project stakeholders, but rather, because it mitigates a high risk scenario that would cause the mission to fail if it occurred. That scenario is the breaking of the turbomolecular pump. The turbomolecular pump is the most expensive piece of the equipment in this project, and it has been generously donated to the project team by the project supervisor. A replacement for this part would cost more than 300% of the project's initial budget, therefore a replacement is out of the question. Therefore, the project team needs to ensure that the proper safety mechanisms are in place to preserve this pump, which is where this requirement comes in.

The deliverable for this requirement was an interface between the electronics driver (Raspberry Pi) and the vacuum system, specifically the roughing and turbomolecular pumps and gauges. An electric circuit is implemented between the two systems that relays data to the computer and also controls the status of the pumps depending on control signals from the Raspberry Pi. This requirement was partially complete in that the Raspberry Pi was able to read data from the gauges and send control signals to toggle a LED; however, a final test on the actual pumps was not able to be performed. Despite this final test being unperformed, the other tests fared well, and it is expected that the final test will reveal that the emergency stopping mechanism is designed and built properly.

P-REG-10 - Radiation Shielding and Safety Modeling

Although this requirement doesn't directly relate to achieving the goal of the project, it is probably the most important. This requirement concerns modelling the radiation parameters of the project and then determining what the necessary shielding is in order to safeguard the project team. It is indirectly related to the project goal because without sufficient radiation shielding, the York University department of health and safety will not allow the operation of the experiment, and thus, the positrons will not be collected. It is crucial that development towards this requirement is performed carefully, as improper procedures taken in the design of the radiation shielding can result in serious injury.

This requirement involves calculating the dose received from the radioactive source at various distances away, and with varying materials between the source and the location of the dose. Due to the criticality of this requirement, these calculations are done by hand, and by computer multiple times, before being further analyzed with various radiation models analyzing softwares. Once a safe shield size is determined, a significant margin was added to ensure the safety of the lab operators. The final design is then to be verified by a representative from the department of health and safety. This representative will inspect the entirety of the lab with special equipment and ensure that the radiation levels do not exceed background levels. Unfortunately at this time, although the radiation shielding model has been made, the project team is unable to verify the design and assembly.

P-PRO-40 - Positron Capture Verification

Similar to the first key requirement listed above, this requirement captures the goal of this project. By meeting this requirement, the project team will have been able to satisfy the secondary needs of the project stakeholders, and will be well on the way to complete the project. At this point, the experimental parts of the project will be complete, and final testing procedures such as user acceptance testing, and lab development procedures will be the only steps left before project completion.

This requirement involves running the entire experiment and analyzing the results to determine if positrons were able to be contained by the system. Essentially, this test combines all the other tests together, but this time requires all tests to work simultaneously. If successful, upon lowering the potential energy of one side of the trapping mechanism, an annihilation result should be picked up by the detection module, and displayed on the lab computer.

3 As-Built Design

3.1 Vacuum System Design

The design of the vacuum had to incorporate two main factors. The first was that we were limited to one turbomolecular pump and the second was that we had to maintain two different pressures within the vacuum system, - 10^{-3} and 10^{-6} torr, respectively. The higher pressure is induced by the injection of nitrogen into a specific section of the vacuum system. Since there are no valves in any part of the system due to the positron beam, we needed to devise a way to maintain both pressures and also keep the higher pressure region isolated from the rest of the system.

For the rest of the system, a pressure of 10^{-6} torr needs to be maintained in order to achieve optimal vacuum states. However, the complication lies within the fact that there is a section in the middle of the system which is at a higher pressure. Unlike viscous flow, where mass transfer occurs from a higher concentration to a lower concentration, in molecular flow (absence of viscosity), mass (in the form of a molecule or atom) can flow in either direction. This makes it imperative that any molecule of N_2 that enters the lower pressure regions of the vacuum system needs to be evacuated as soon as possible. In order to do so, the top of the system needs to be directly connected to the turbomolecular pump as well. When this is achieved, it lowers the probability of any adsorption or stimulated desorption that might ensue due to any lingering nitrogen atom in those specific low pressure regions. The change in pressure near the top of the system is most crucial as it is the farthest from the turbomolecular pump and also the closest to the nitrogen injection system, relative to the rest of the system. In order to ensure that part of the system will be at the desired pressure, a micro-ion gauge is mounted. If the gauge reads the desired pressure at the top, then it is understood that all other sections and regions are also at that desired pressure of 10^{-6} torr (apart from 10^{-3} torr for the nitrogen injection system), since they are much closer to the TMP.

Figure 3.1 and Figure 3.2 below show the potential design of the entire vacuum system assembly along with the corresponding magnetic field coils (in brown).

***Figure 3.1**: Antimatter containment unit (CAD Design)*

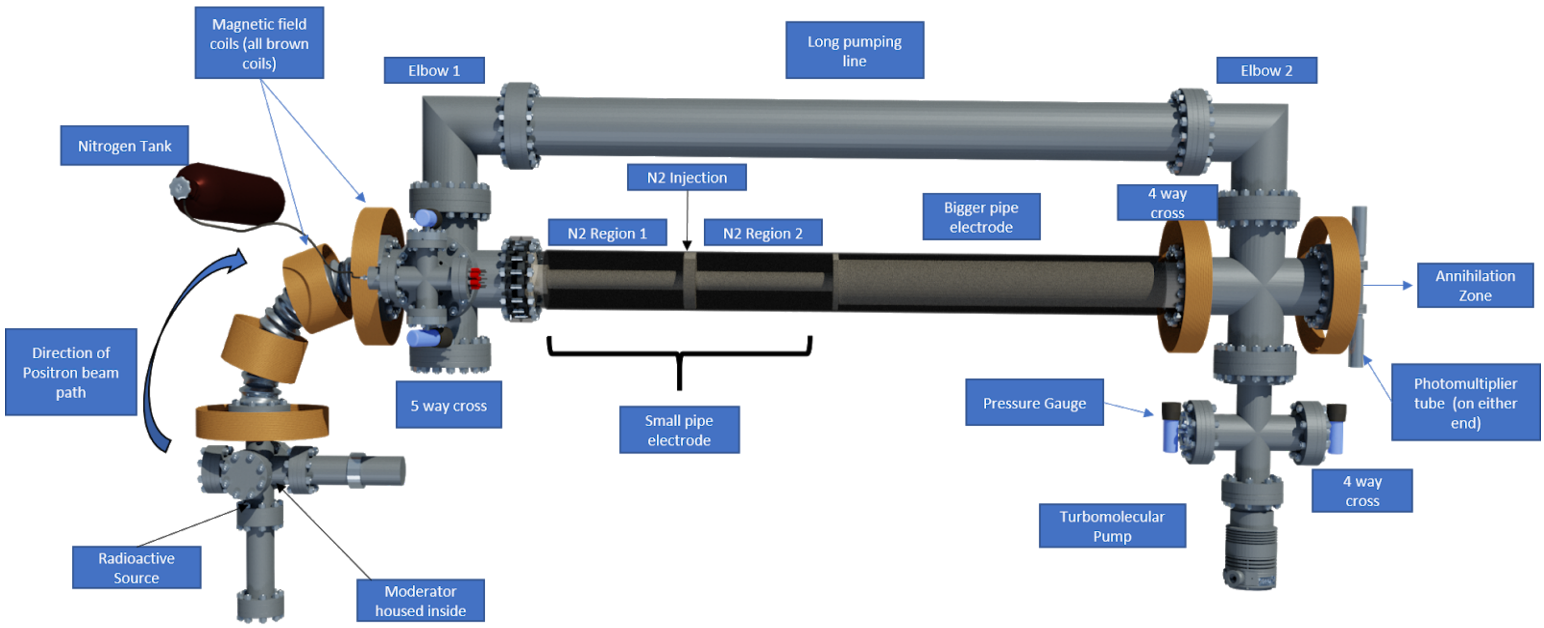

***Figure 3.2**: Labelled figure of entire experimental setup*

Figure 3.1 and Figure 3.2 outline the intended design if the required funding is available, and all the parts are in possession. The radioactive source will be in the bottom left of the figure. The positrons will be emitted from the radioactive source and travel through the bend, guided by the magnetic fields. The reason why there is a bend is to isolate the high energy positrons from the low energy positrons. Only the low energy positrons will go through the system and into the 5-way cross and into the nitrogen regions. If there's a situation where the positrons shouldn't be moderated, the moderator can be removed from the middle and all the positrons will hit the lead shielding.

The reason why there is a second pipe (long pumping line) is to connect the turbomolecular pump to the left hand side of the system and maintain two pressure regions. The nitrogen region should be at 10^{-3} torr and the rest of the system should be at 10^{-6} torr. This will allow both regions to be at the desired pressure values. One of the limitations of this is that since nitrogen gas will be injected into the system, there will be a larger pressure gradient compared to a system if two turbomolecular pumps were available.

The size of the large length tubes and solenoids are 48 inches in length and have an outer flange diameter of 6 inches. The system is small enough to fit on a lab table of size of 121cm x 183cm (table 1) with the annihilation zone resting on a table of size 61.5cm x 91cm (table 2). The radiation shielding will also be placed on the 121cm x 183cm table. This can all be seen in Figure 3.21, Figure 3.24 & Figure 3.32.The full dimensions of all parts can be seen in Section 9, Project Procurement. Everything to the right of the 5-way cross must have a flange outer diameter of 6 inches. This is to reduce conductance which will help with the flow in the system. The only way to control conductance in this case is by controlling the geometry and shape of the pipes. So it was decided to use 6 inch elbows and 6 inch 4-way crosses to simplify the system and maintain a reasonable conductance. Conductance will be discussed in further detail in Section 3.2, Nitrogen Injection System Design.

The positron will travel through the nitrogen region, lose energy through the interactions it has with the nitrogen gas and get trapped in the “Bigger Pipe Electrode”.When the trap is turned off by stopping the flow of electricity in the electrode, the positrons will flow towards the annihilation zone.

Figure 3.3 below shows the assembly drawing for the system

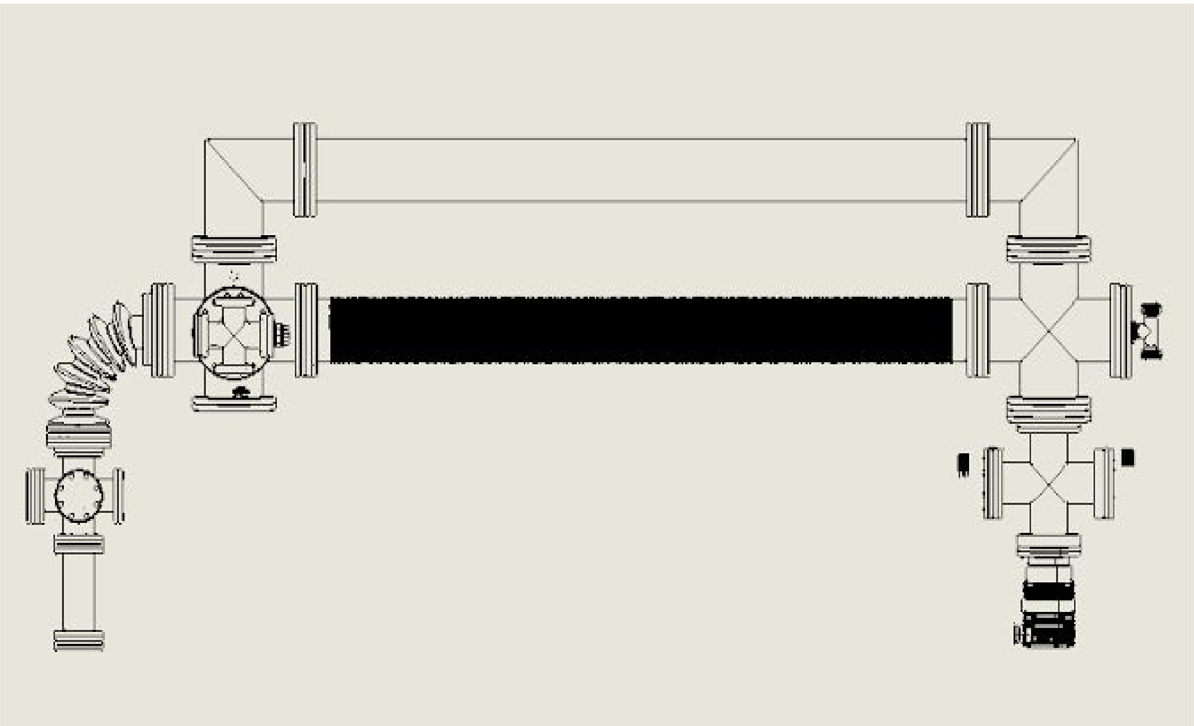

***Figure 3.3**: Assembly drawing*

The figures below show the as-built model of the system. As seen, the physical model is not fully complete due to the current pandemic along with project procurement delays. More information about the missing components can be seen in Section 9, As-Built Project Procurement/Equipment/Travel list.

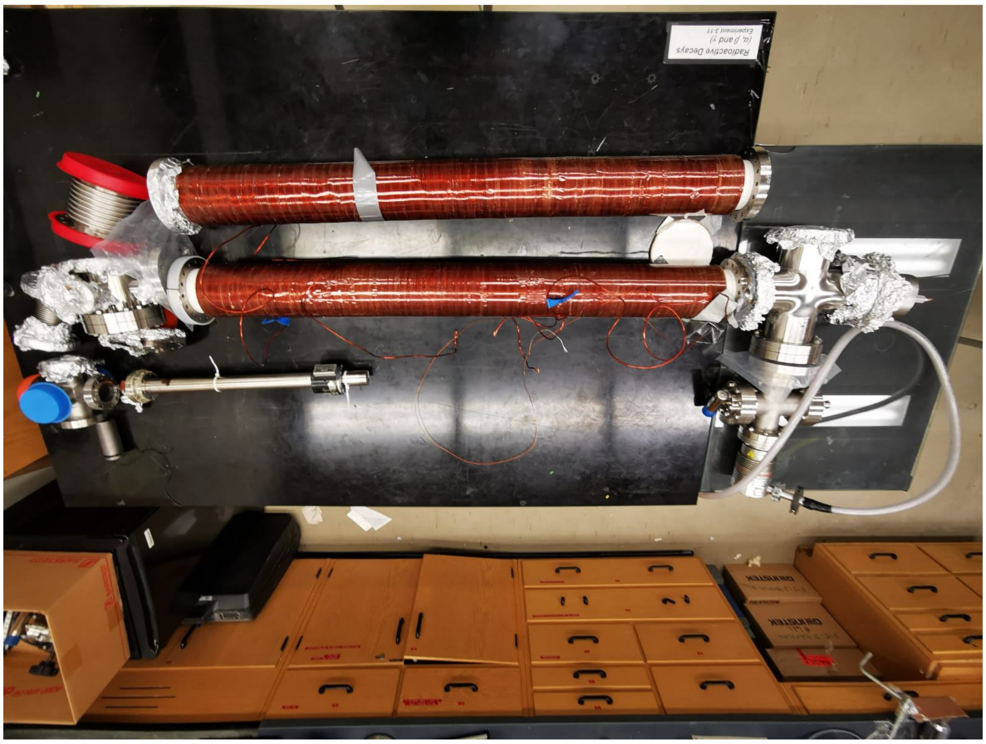

***Figure 3.4**: Top view of as-built containment unit*

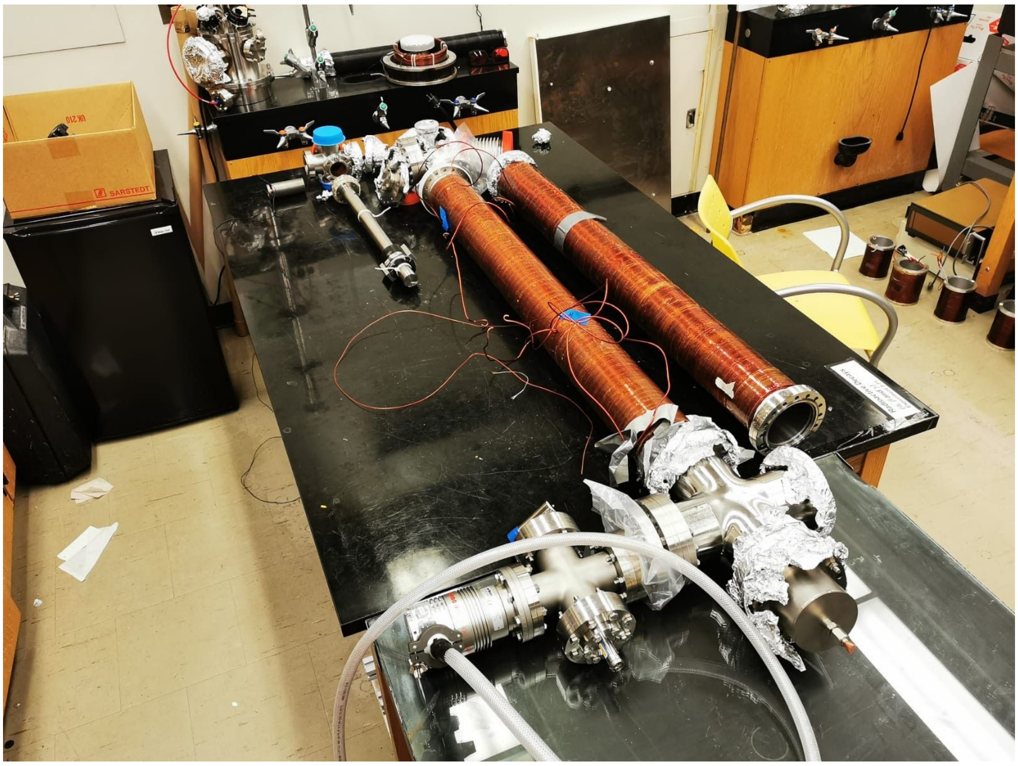

***Figure 3.5**: Isometric view of as-built containment unit*

3.2 Nitrogen Injection System Design

As stated in the vacuum system design section, modelling a vacuum system is difficult unless you use specialized software that does it for you. You can use molecular flow principles but it becomes very tedious and time consuming, as every section of the system will require its own formula for conductance and depending on the geometry the final equation that is needed to be solved becomes a coupled partial differential equation which is not always solvable. However there is another way to model a vacuum system as discussed below.

In traditional fluid mechanics, gas flow regimes are recognized by the type of gas along with the amount of gas that is flowing through a pipe or system. In order to describe the gas characteristics we calculate the Knudsen's Number given below.

$$Kn = \frac{\lambda}{d} \tag{1}$$

Knudsen's number is a dimensionless ratio of the molecular mean free path length, represented by the greek letter lambda, to the physical length of the pipe,d, (can be in terms of diameter or some other physical length scale).
On the other hand in order to describe how the flow is moving we calculate the Reynolds' number given below

$$R = \frac{U\rho d}{\eta} \tag{2}$$

Here, *U* represents flow velocity m/s, ρ is mass density kg/m^3 of the gas, η is gas viscosity and d is the pipe diameter. Reynolds' number is also a dimensionless entity and describes the relationship of a fluid's inertial forces over its viscous forces. When Knudsen number is below 0.01, the flow is characterized by viscosity and is termed as continuum flow. What this essentially means is that the diameter of the pipe is much larger than the molecular mean free path of the gas, and such a flow is determined by gas-gas collisions. Continuum flow further is characterized by the fluid's ability to either flow gently past obstructions in laminar streamlines. If the flow is able to do that then it is termed as laminar but if the velocity is much higher then it will flow past obstructions in a chaotic manner. In this case, the flow will be termed as turbulent. Reynolds' number characterizes and differentiates whether a flow is laminar, turbulent or within the transition region. Typically for flow within a pipe, laminar flow exists when Reynolds' number $<$1200, the transition period is between 1200 to 2200 while anything above 2200 is turbulent flow.

Due to the equation for Renolds' number which gives a relationship between inertial forces over viscous forces, it can be seen that laminar flow is always dominated by viscous flow. When we are dealing with laminar viscous flow Knudsen number is less than 0.01. But within laminar flow if the mean free path of the gas is equal to the pipe diameter then

Knudsen number equals 1. At this point the flow is no longer characterized as viscous anymore and is said to be molecular instead.

Within molecular flow Reynold's number has no meaning as the gas is now within a free-molecular regime where classical viscosity can no longer be defined[1]. Molecular flow is a lot different to viscous flow, as instead of gas-gas collisions, gas-wall collisions dominate and viscosity as a concept does not exist. Molecular flow is one of the most understood of the 3 types of flow and due to that, there is a lot of literature on the topic. In molecular flow diffuse reflection at the wall is a good approximation for most surfaces. This means that a particle arrives, sticks, rattles around in surface imperfections, and is emitted in a random direction independent of its incident velocity[2]. Molecules in molecular flow do not collide with each other and the gas can flow in either direction simultaneously without coming into contact with each other. Since gas flow is defined differently within this flow regime, the definitions of mass flow, throughput and conductance will also need to be re-defined.

Throughput is defined as the amount of gas that passes through a plane in a given time at a known pressure. Its formula and units are as follows: $d/dt(PV) = Q$; Pa-m^3/s. But because of 1 Pa = N/m^2 and 1 J = N m, the throughput units can be expressed as J/s or watts. One cannot get mass flow from throughput without specifying the temperature. It is not intuitive to think that throughput is the same as watts, but when converting every other aspect of a vacuum system into an electrical circuit, it definitely helps out.

The flow of gas in a pipe is entirely dependent on the geometry of the cross sections along with the pressure drop induced through the object. As you divide throughput by the induced pressure drop through the object while the temperature is stagnated at a constant level, a property known as the conductance of the pipe is yielded:

$$C = \frac{Q}{P_2 - P_1} \tag{3}$$

The units for C are m^3/s, this if broken down is m^2*m/s or area*velocity. Flow rate through a pipe (*Q*) is analogous to current within a circuit (I) as they are both in terms of time. On the other hand, pressure is potential stored in the pipe. This pressure difference is what drives flow in that pipe. If there is no pressure difference then there will be no flow. This is analogous to how voltage affects an electrical circuit. Voltage is the stored potential within a circuit. A difference in voltage induces current to flow while no difference in means current will not flow. So the above equation for conductance is simply the current divided by voltage (I/V). According to the formula V = IR, when solved for R is V/I. This means that conductance is inversely proportional to resistance and hence is equal to 1/R. Similar to electrical charge flow, gas conductance can be nonlinear and a function of pressure at times due to the type of flow (transition, viscous or choked) being experienced.

Below is the electric equivalent circuit for the nitrogen gas injection module

[1] Page 26 O'Hanlon, J. F. (2003). A User's Guide to Vacuum Technology (3rd ed.). Wiley-Interscience.
[2] Page 26 O'Hanlon, J. F. (2003). A User's Guide to Vacuum Technology (3rd ed.). Wiley-Interscience.

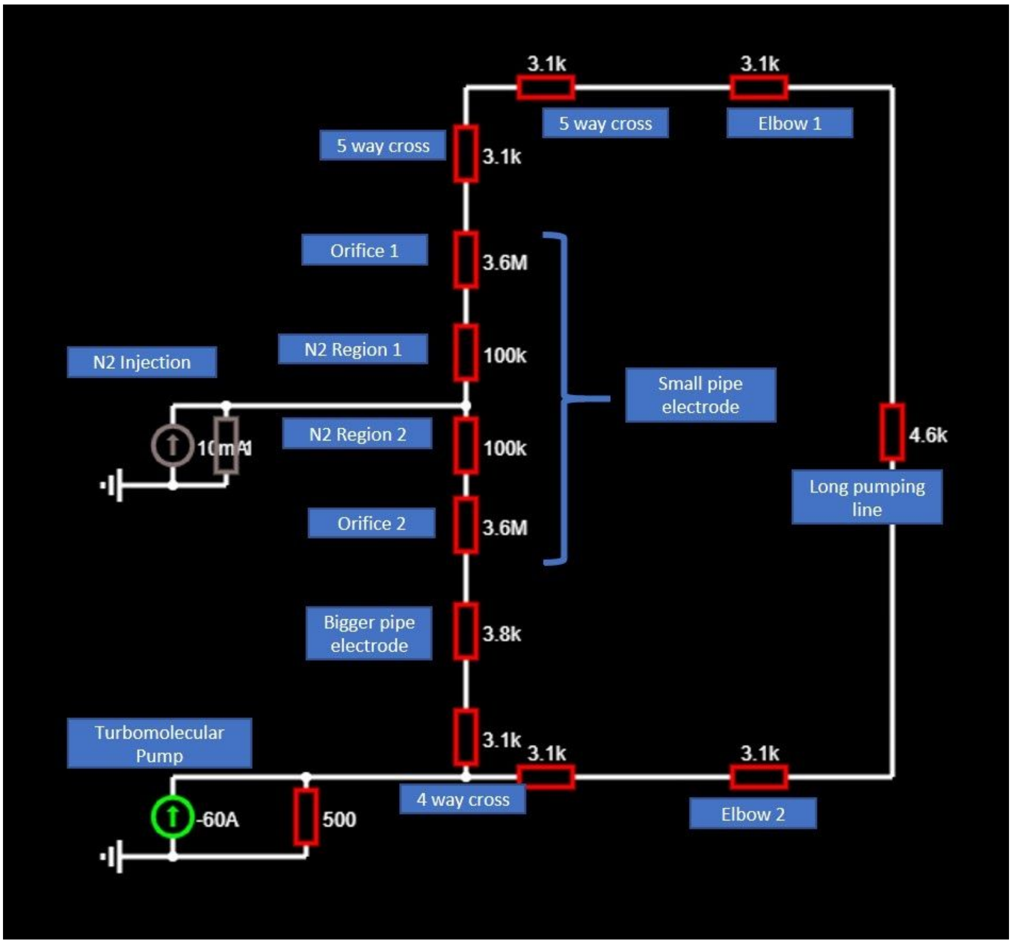

***Figure 3.6**: Nitrogen injection system circuit model*

As seen in the above figure, the resistors represent the specific sections of the system setup. The values of the resistors were all based in reference to the 'Small electrode pipe" or the nitrogen region 1 and 2. Over here we assumed a reference value of 100 x10^3 ohms for nitrogen region 1 and 2. The total assumed base reference value of the small pipe electrode is 200 x10^3 ohms. There are 2 orifices at the entrance and exit of the small pipe electrode (nitrogen regions 1 and 2 combined) in order to induce a pressure difference of 1000 and have the small pipe electrode at 10^{-3} torr in pressure while the rest of the system is at 10^{-6} torr. In order to model the size of the electrode we need to relate drop in conductance given the system geometries to the increase in resistance within the circuit. Theoretically an orifice has an infinite length and hence as infinite resistance. For our practical application the orifice carries a small amount of length; enough to mount it into the electrode assembly. However the impact on the resistance to flow from this small length is negligible. In practical applications, the area of the orifice is the driving factor in terms of influencing the conductance and hence the pressure distribution. This can be further visualised by the following formula

$$C = 3.64 \times A \times \sqrt{\frac{T}{M}} \text{ (1/sec)} \quad (4)$$

Where

C = conductance in m^3/s

A = area of orifice in cm^2

T = temperature in Kelvin

M = Atomic mass unit of gas flowing (for N_2, M=28)

A simplified version of the above formula of Nitrogen at 20℃, where A = cm^2

$$C = 11.6 \times A \quad (5)$$

For long pipes

$$C = 12.1 \times D^3/L \quad (6)$$

Where

D = inner diameter of pipe in cm

L = length of pipe in cm

The resistor value for the 2 orifices in the electrical circuit is at 3.58 x 10^6 ohms. When referenced back to the small pipe electrode resistance of 200 x10^3, it can be seen that the orifice's resistance is 17.92 times higher than the small pipe electrode. As the conductance equation of an orifice is dominated by its area; it can be extrapolated that the orifice area is 17.92 times smaller than the diameter of the small pipe electrode.

In the current design, the diameter of the small pipe electrode is 1 in or 2.54 cm. This electrode was part of the equipment donated to this project from the physics department. In order to get an area reduction of 17.92 times, the corresponding radius of the orifice will need to be 0.3 cm or a total diameter of 0.6 cm. This orifice will be implemented on both ends of the small pipe electrode.

The combination of the 2 orifices and the 2 nitrogen regions provides a voltage difference of 1000 when compared to the voltage at the bigger pipe electrode. As explained above, voltage is analogous to pressure and so if we are seeing a voltage difference of 1000 times within modelling then we can expect a similar outcome in real life. It will not exactly behave like the model but we will be in the correct order of magnitude and then further optimise to reach the desired pressure levels. In order to achieve this voltage difference, the current source inputted was 10mA. For this simulation, the base for current is set at 1A = 1 L/s which means that in order to strive for this pressure difference the nitrogen will need to be fed into the system at 10mL/s.

The resistor values of the other components of the circuit are derived as follows:

The bigger pipe electrode diameter is 2.98 in or 7.57 cm. Using the conductance equation for long pipes and relating this to the conductance of the small pipe electrode (diameter of 1 in or 2.54 cm where - both of the nitrogen regions are combined), it can be seen that their conductances are dependent on the diameter. Within the design of the small and big pipe electrodes, their total length is assumed to be the same in calculation (even though the bigger pipe electrode is a little longer than the smaller one in actuality). This is due to many reasons. The first being that we have been limited in terms of the total length of this system. Secondly it is very important to have a uniform magnetic field for positron trapping purposes as it greatly increases efficiency and probability of trapping them within the system. Thirdly, these long pipes were part of equipment that the Physics department donated towards this project. The small pipe electrode was also donated to the project from the Physics department. It was used within the trapping mechanism of the Antihydrogen Trap experiment which York University collaborated on with other institutions at CERN. Along with that, we were dealing with 2 pressure regions and only had one turbomolecular pump on hand, and so we needed an exact shape and sized pipe going back the other way and act as a flow re-router. This pipe would connect the two opposite ends of the system with each other. The Physics department had 2 of these pipes as previously mentioned and so this fit our needs well. However it should be noted that we were only made aware of the availability of the pipes and the small pipe electrode in mid January and so a design change of the entire assembly followed. This design change was influenced by the need to minimise expenses as well as keep the system as symmetric as possible so that a more uniform conductance can be developed throughout.

The bigger pipe electrode's conductance value is dominated by its diameter as mentioned before. The conductance equation for a long pipe has a D^3 term in it.

Hence: $(D_{\text{Bigger pipe electrode}})^3/(D_{\text{Small pipe electrode}})^3 = (7.569\text{ cm})^3/(2.54\text{ cm})^3 = 26.46$

This then denotes a resistor value of the bigger pipe electrode to be 26.46 times smaller than the nitrogen region or in other words, the bigger pipe electrode has a conductance that is 26.46 times higher than the small pipe electrode From this we get $100 \times 10^3/26.46 = 3780$ ohms for that resistor.

Typically an elbow and a 4 or 5 way cross cuts the conductance by 50% when compared to the same diameter long pipe. Our design uses a 6 in or 15.24 cm OD and 4 in or 10.16 cm ID piping system for the majority of the assembly. Applying the same relative diameter ratios as above we get a conductance difference of 64 with reference to the small pipe electrode (ID 1in or 2.54 cm). When applying this difference to the small pipe electrode and the 50% loss of conductance (which means double the resistance) we get a resistor value for the crosses and the elbow to be 3125 ohms.

Finally, the long pumping line pipe undergoes a loss of conductance when compared to the bigger pipe electrode. It should be noted that the bigger pipe electrode (7.569 cm ID) is half the length of the pumping line pipe (10.16 cm ID). When taking these dimensions into account and solving for the ratio between them, (through the long pipe conductance) equation, the value we get is 1.21. This means that the long pumping line tube has a conductance 1.21 times smaller or the resistance being 1.21 times bigger than that of the bigger pipe electrode. This then gives the resistance value of the long pumping line to be 4571 ohms.

A model of the nitrogen molecules colliding with positrons is currently being developed and will be made available once to complete.

3.2.1 Trapping Mechanism Design

The trapping mechanism is used to load, confine and manipulate the positrons. As the positrons move through this nitrogen region, they will transfer kinetic energy to the nitrogen atoms (if the positrons have a kinetic energy of 7.5 eV more than the Nitrogen gas). This interaction is probabilistic and increases with the number of nitrogen atoms present, and the time spent inside this nitrogen region. After the interaction, the nitrogen atoms get excited and the positrons lose kinetic energy. It is important to note that after the interaction, the positrons will annihilate when they collide with nitrogen, as they no longer have the required energy difference needed for the desired interaction. The lifetime of positrons in this situation is mainly dependent on the number of nitrogen atoms present, as more nitrogen equals more annihilate interaction.

In order for the trap to work, 2 types of electrodes are planned on being used, the smaller pipe electrode will house nitrogen gas and the bigger pipe electrode will be the final trapping region that the positrons oscillate within before heading towards the annihilation point. Each region is set to be 7.5 V below the previous region, and also has a pressure difference of up to 1000 times. A combination of voltage potentials will be used to trap the positrons within the system. Due to the magnetic field, the positrons also go through some radial motion. At this point, the positrons will have slowed down a lot and are going back and forth in the trap centre.

Once the positrons have entered the nitrogen region, an inelastic collision will lower its energy level and it will then begin oscillating within the confinements of the trap. It won’t be able to leave the small pipe electrode due to the combination of voltage potentials used. On the other end of the bigger pipe electrode there will be a high voltage wall at around 50eV. This will prevent the positrons from leaving the trap from that side. The lowered energy positrons will now be oscillating back and forth. Another collision will have the positrons’ energy lowered further than this will make them go down another energy step (as seen in Figure 3.7). As stated before the 50ev high voltage wall at the end confine the positrons to the second stage of the trapping process. This wall serves as an energy loss mechanism which is required because any positron that has enough energy to enter the trap, also has enough energy to leave. The positrons continue to lose axial kinetic energy. When we have trapped the positrons for as long as required, the potential of the wall will be decreased, and the positrons will be able to leave and enter the annihilation zone and subsequent detection.

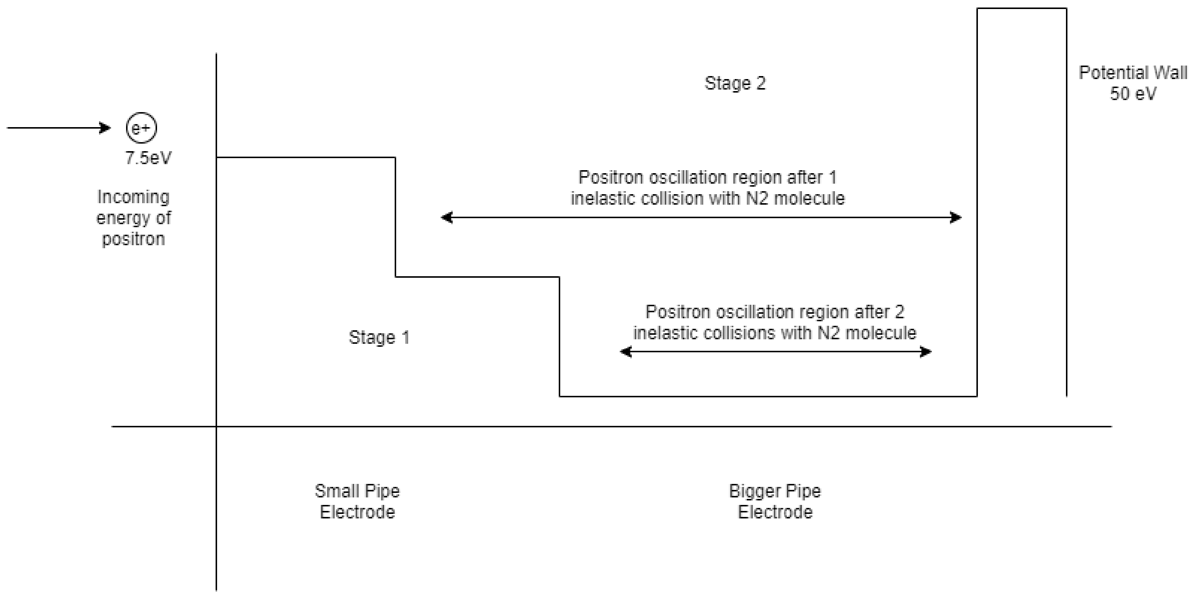

***Figure 3.7**: Positron trapping within 2 electrodes*

3.2.2 Electrode Model

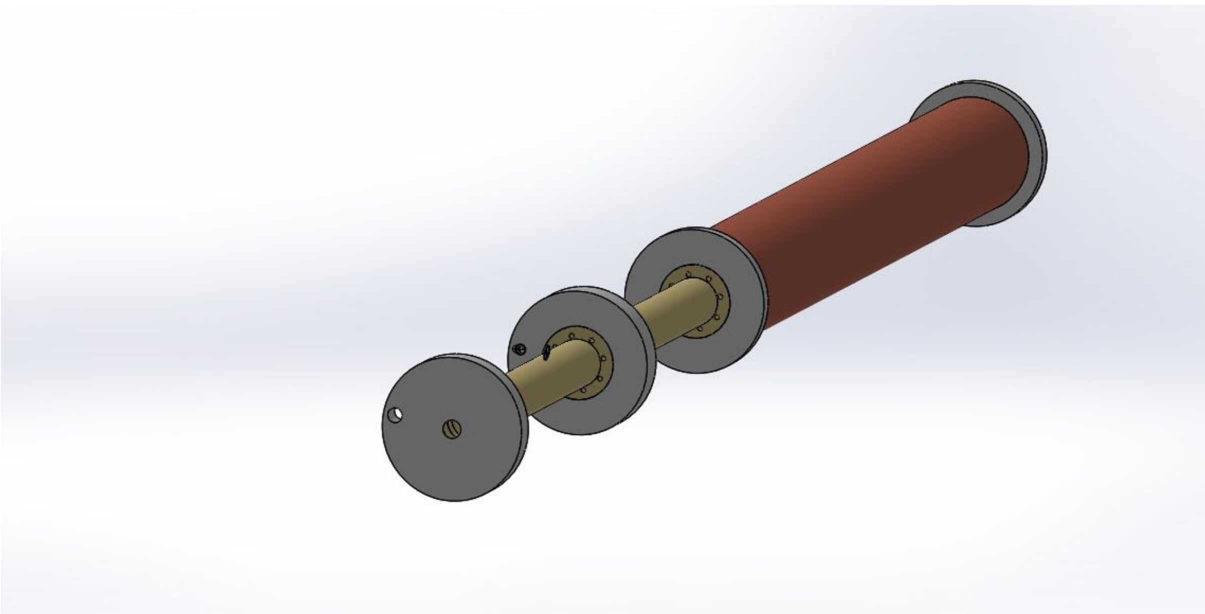

***Figure 3.8**: Electrode (view 1)*

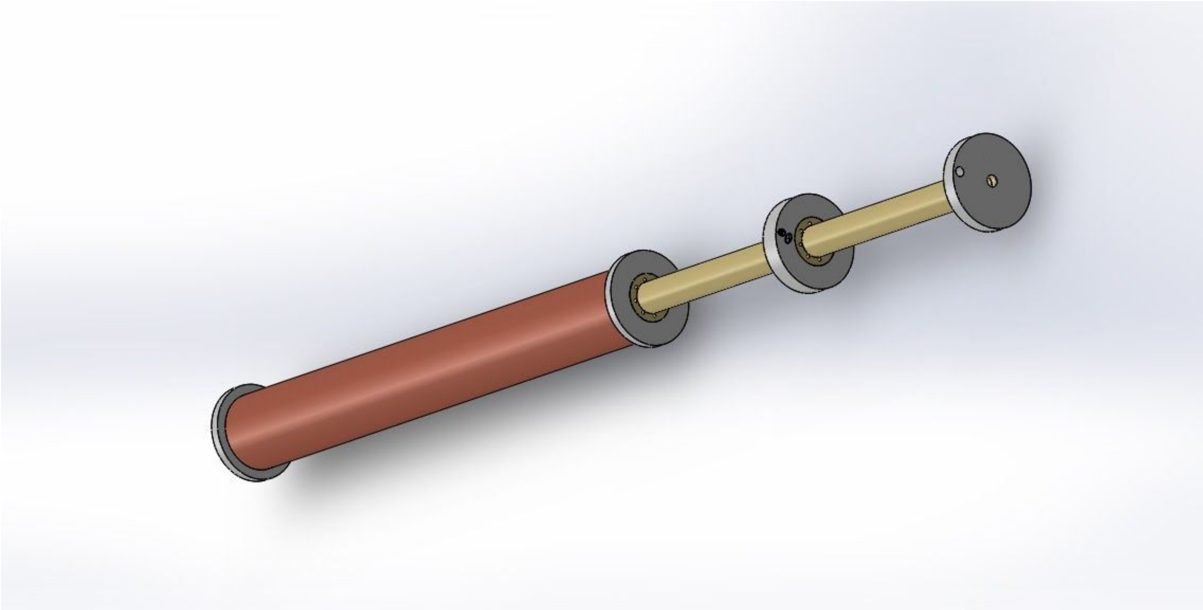

Figure 3.9: Electrode (view 2)

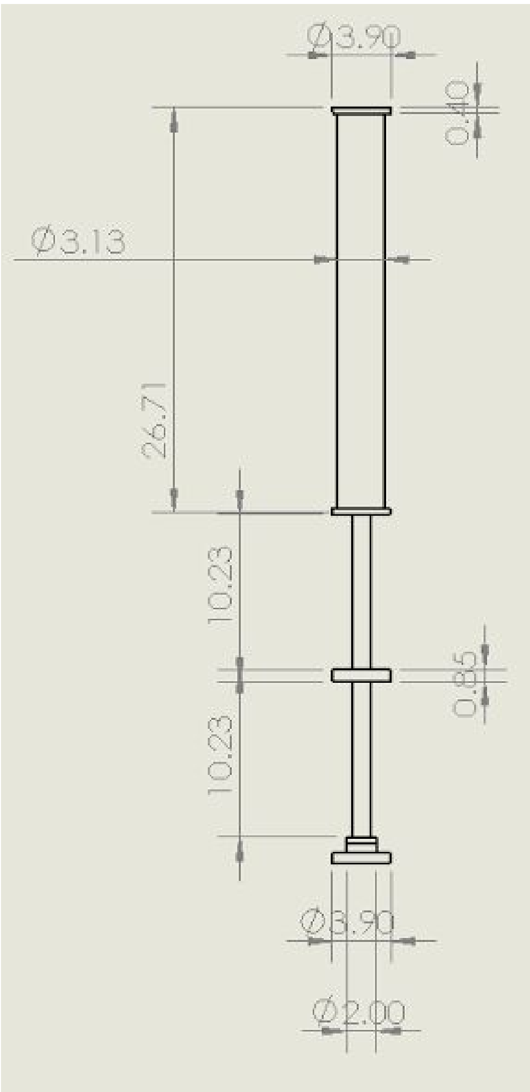

***Figure 3.10**: Electrode CAD drawing*

***Figure 3.11**: As-Built Electrode*

3.3 Radioactive Source

The positrons are being emitted from Sodium-22 (Na22) through beta decay, along with gamma rays and beta particles[3]. This source was provided to us by the Physics Department. The strength of the source is about 5.2 millicurie (miC) and emits 170 million positrons per second [4]. The positrons are emitted with kinetic energies ranging from 0eV to 500keV[5]. However, due to the inner processes of the moderator and its ability to slow down positrons, only 15 million positrons per second will be available for the purpose of trapping.

3.3 Radioactive Source Housing

The radioactive source is housed inside a Copper-Tungsten alloy. This housing was chosen mainly for the low outgas rate and the ability to shield from the radioactive byproducts. At the pressures that the housing will be under, plastics and other similar materials will have a high outgassing rate, this will destroy the vacuum created and annihilate the emitted positrons instantly. This alloy has an extremely high density, 17 grams per centimeter cubed [6], and a high atomic mass, which makes it a good radioactive shield. Gamma rays are best absorbed by a heavy atomic nucleus, and Tungsten has an atomic weight of 180.94 amu [7], only 100 amu less than lead [8]. Lead is the most common radiation shielding used for gamma rays due to its high atomic mass. The alloy has the ability to stop beta particle particles proportional to its density.

The housing is a cylindrical shape, which is 10 cm tall and has a radius of 7 cm. There is a hole carved out, about 1 cm deep and with a radius of 3 cm. This hole is where the source will be placed.

3.5 Moderator

As mentioned before, the emitted positrons have a large amount of kinetic energy, and are very difficult to handle in a controlled manner. For this reason, we are using a moderator which will slow down the positrons from the maximum energy level of 500 keV to about 1 to 2 eV. Note that in Figure 3.13, the full width half maximum (FWHM) has become smaller after passing through the moderator. There is less spread in the velocity distribution

[3] Page 19 D. Comeau. ATRAP Buffer-gas positron accumulator. Thesis, 2014
[4] Page 20 D. Comeau. ATRAP Buffer-gas positron accumulator. Thesis, 2014
[5] Page 27 D. Comeau. ATRAP Buffer-gas positron accumulator. Thesis, 2014
[6] "Tungsten Alloy." *Tungsten Alloy Properties Custom Machined Products*, https://www.tungsten.com/products/tungsten-alloy/.
[7] Bentor, Yinon. *Chemical Elements.com - Tungsten (W)*, http://www.chemicalelements.com/elements/w.html.
[8] Bentor, Yinon. *Chemical Elements.com - Lead (Pb)*, http://www.chemicalelements.com/elements/pb.html.

and therefore, a smaller range of velocities. The moderator we are going to be using is a Tungsten crystal, which has also been provided to by the Physics department.

The moderator will not slow down all the positrons going through it. It will slow down about 1% of the incoming positrons, and the rest will go straight through and annihilate at the end of the surface, as illustrated in Figure 3.12. The slowed positrons at the end of the moderator will be at an energy level of 1 to 2 eV and will be accelerated away from the moderator. This will happen by setting the moderator to a positive voltage of about 6V. The positron's kinetic energies will increase from 1-2 eV to about 7-8 eV. The increase in the kinetic energy is needed so that positrons are 7.5eV above the nitrogen gas, which is needed for the buffer gas trapping method. With this, we expect about 150 000 positrons to be sent towards our trapping mechanism per second. The moderator will need to be cleaned as the positrons will create electrons-holes in the crystal structure.

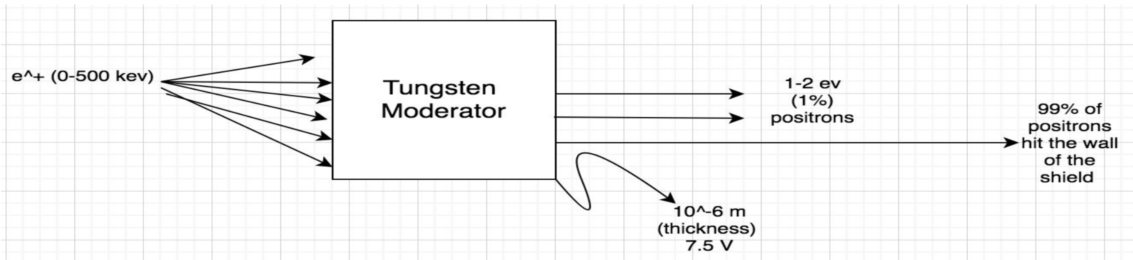

***Figure 3.12**: Positron Interaction with the Tungsten Moderator*

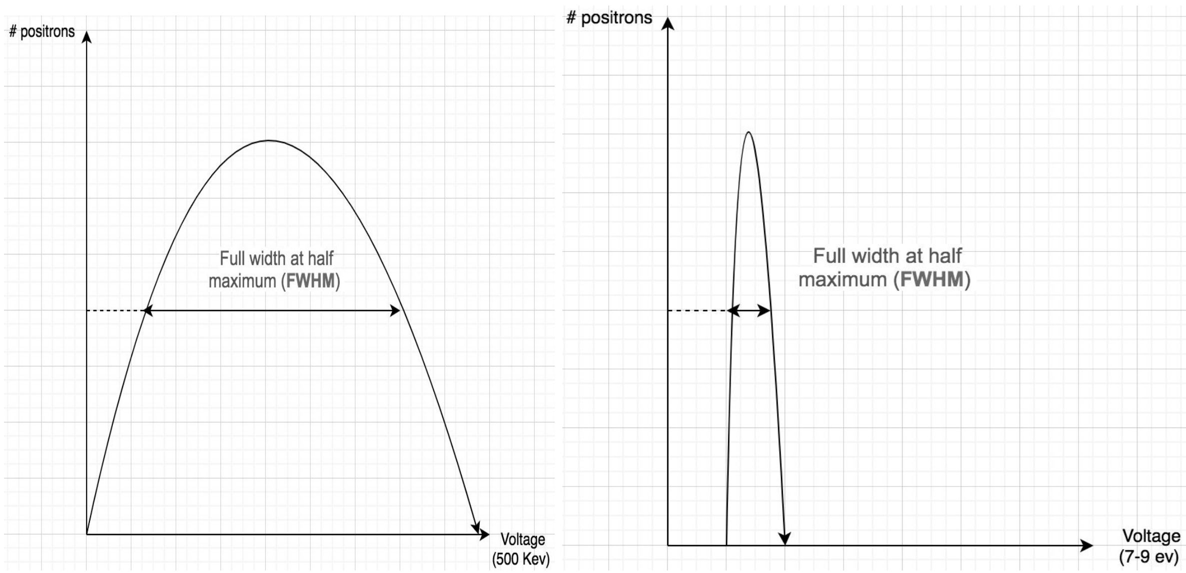

***Figure 3.13**: The FWHM before and after penetrating the Tungsten Moderator*

3.6 Magnetic Field System

The positrons emitted from the moderator will have kinetic energies ranging from 7-9 eV. As mentioned earlier, to make sure that the positrons don't hit the walls, the radius of the collimated beam needs to be very small. The smallest tube that the positron beam will go through has a radius of 6.35 cm. Considering the speeds of the positrons, the minimum magnetic field needed to impede positron-wall collisions is calculated to be approximately

4.25 Gauss. To concentrate the beam and achieve beam collimation, 100 Gauss will be used.

Using the coils provided, an approximately steady magnetic field of 100 Gauss will be generated along the positron beam's path. A MATLAB model will be created to decide the orientation of the coils for a consistent magnetic field for the positron beam's path.

Coils

For the assembly of the magnetic field system, the following types of coils will be used.

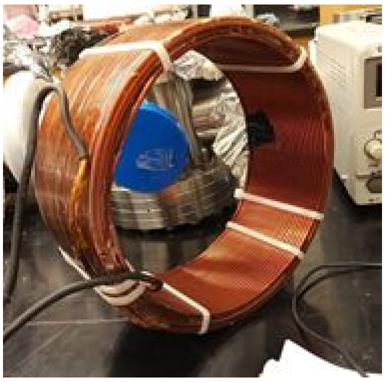

Figure 3.14: *Coil A*

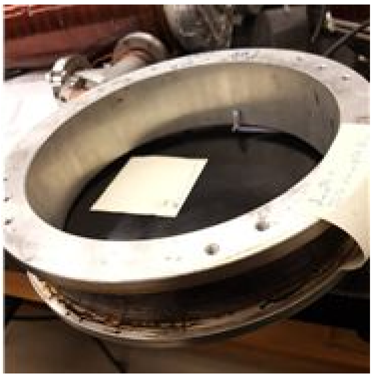

Figure 3.15: *Coil B*

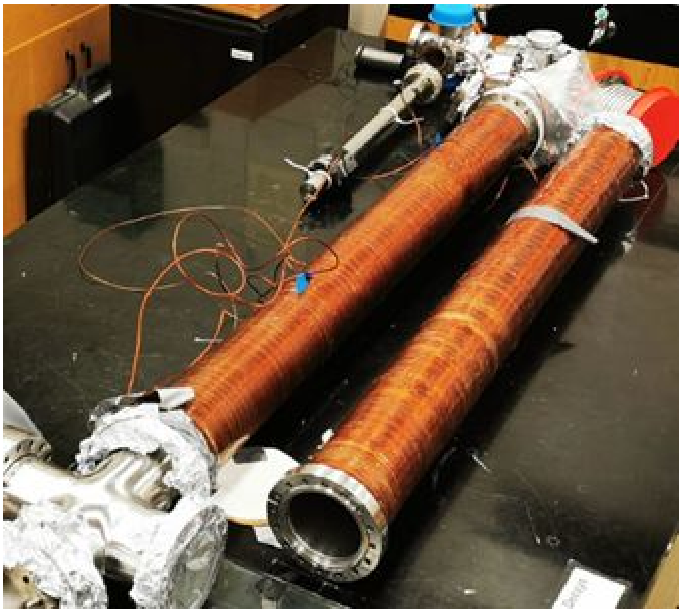

Figure 3.16: *Coil C*

***Table 3.1**: Dimensions of all coils*

	Coil A	Coil B	Coil C
Length (cm)	7.62 ± 0.02	3.8 ± 0.1	117.5 ± 0.1
Radius (cm)	7.0 ± 0.2	12.05 ± 0.01	5.08 ± 0.01

To calculate the number of turns N for each of the coils, the magnetic field B produced at the centre is measured when a current I is supplied. Using Equation 7 the following data is obtained.

$$I = \frac{BL}{\mu N} \tag{7}$$

For coil A,

***Table 3.2**: Calculation of number of turns for coil A*

I (A)	B ($*10^{-4}$ T)	N
5	33.0 ± 0.5	40.1 ± 0.6
4.5	23.07 ± 0.04	31.09 ± 0.05
4	26.08 ± 0.05	39.54 ± 0.08
3.5	23.85 ± 0.07	41.3 ± 0.1
3	19.40 ± 0.08	39.21 ± 0.2
2	12.7 ± 0.05	38.5 ± 0.2
1	6.91 ± 0.07	41.9 ± 0.4

Taking the average, the total number of turns in coil A is 40.09 ± 0.02.

Solve for the current needed to generate 100 Gauss, we get:

$$I = \frac{BL}{\mu N} = \frac{(100\times10^{-4}T)(0.0762m)}{\mu(40.09)} = 26.9\ A$$

For coil B,

***Table 3.3**: Calculation of number of turns for coil B*

I (A)	B (*10^{-4} T)	N
5	38.62 ± 0.07	23.35 ± 0.04
4.5	35.57 ± 0.05	23.90 ± 0.03
4	31.8 ± 0.02	24.04 ± 0.03
3	24.12 ± 0.01	24.31 ± 0.01
3.5	27.42 ± 0.02	23.69 ± 0.02
2	15.83 ± 0.02	23.93 ± 0.03
1	8.18 ± 0.02	24.74 ± 0.06

Taking the average, the total number of turns in coil B is 24.0 ± 0.1.

Solve for the current needed to generate 100 Gauss, we get:

$$I = \frac{BL}{\mu N} = \frac{(100\times10^{-4}T)(0.038m)}{\mu(24.0)} = 12.6\ A$$

For coil C

***Table 3.4**: Calculation of number of turns for coil C*

I (A)	B (*10^{-4} T)	N
5	87.3 ± 0.7	1625.63 ± 13.03
4	70 ± 1	1629.35 ± 23.28
3	52 ± 1	1613.83 ± 31.04
2	35.0 ± 0.5	1629.35 ± 23.27
1	17.5 ± 0.3	1629.35 ± 27.93

Taking the average, the total number of turns in coil C is 1630 ± 20.

Similarly, for coil C, we use the same equation to solve for the current needed to generate 100 Gauss:

$$I = \frac{BL}{\mu N} = \frac{(100\times10^{-4}T)(1.175m)}{\mu(1626)} = 5.75\ A$$

Elevation:

To have the magnetic field at the centre, the green and read coils will have to be elevated by a couple centimeters. Relative to coil B, the coil C will have to be elevated by at least 7.57 cm (2.98 inches).

Calculation:

Radius of coil B - radius of coil C = 25.3/2 - 10.16/3 = 7.57 cm

Similarly, the elevation for the coil A must be at least 5.65 cm (2.22 inches).

Calculation:

Radius of coil B - radius of coil A = 25.3/2 - 7 = 5.65 cm

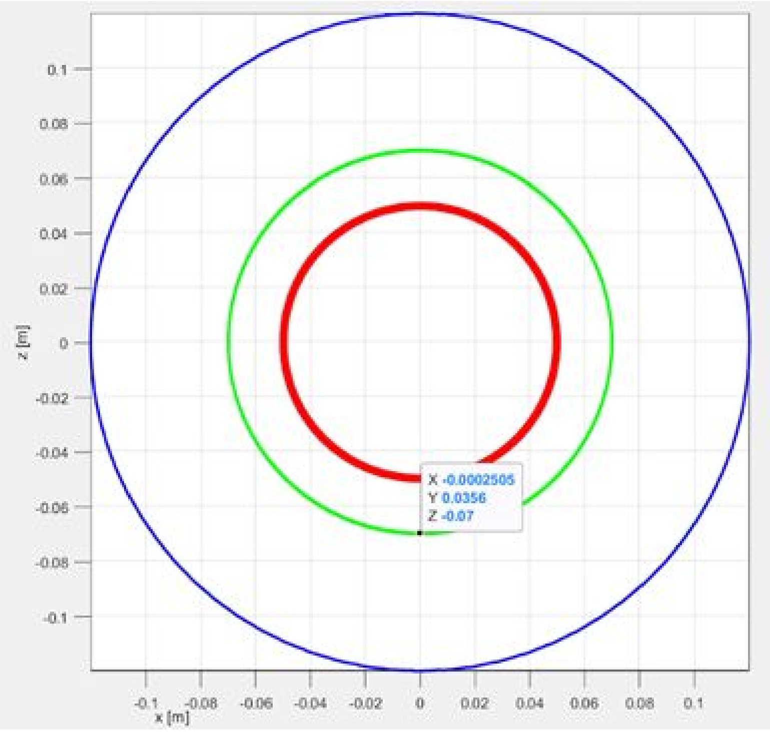

***Figure 3.17**: Diameter comparison of the coils*

Computer Model

The model is created using MATLAB. First, the points of the coil using a rotation matrix are defined in cylindrical coordinates. These points are then plotted using the default plot function.

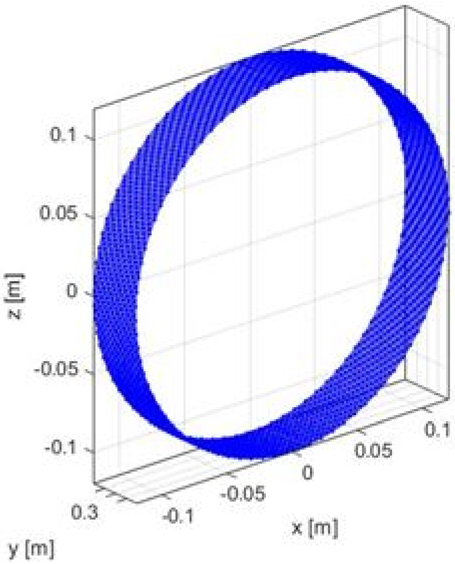

***Figure 3.18**: Plot of coil B*

The points of the coil are discretized. A created function is used which takes in the points of the coil and the current for the input, and gives a current carrying coil as an output. This is repeated for all the coils. Using the mesh grid function, a 3D mesh grid is defined and points where the magnetic field is to be calculated are plotted. Then, another function is created that takes in the coordinates of the points and current carrying coils as the input, and outputs the components of the magnetic field at those points, using Biot-Savart integration. Finally, the resultant of all the components of the magnetic fields of the coils is calculated and the quiver function is used to get the direction of the magnetic field, on the points in the mesh grid, to get the final visual of the magnetic field on the model.

Results

The final result of the model are as follows:

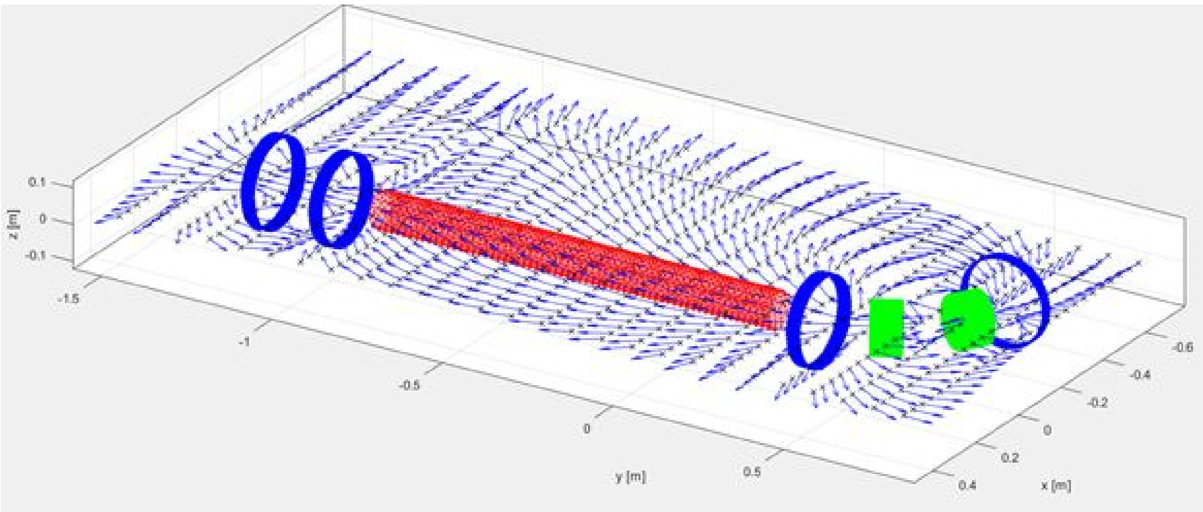

Figure 3.19*: Side view of the model*

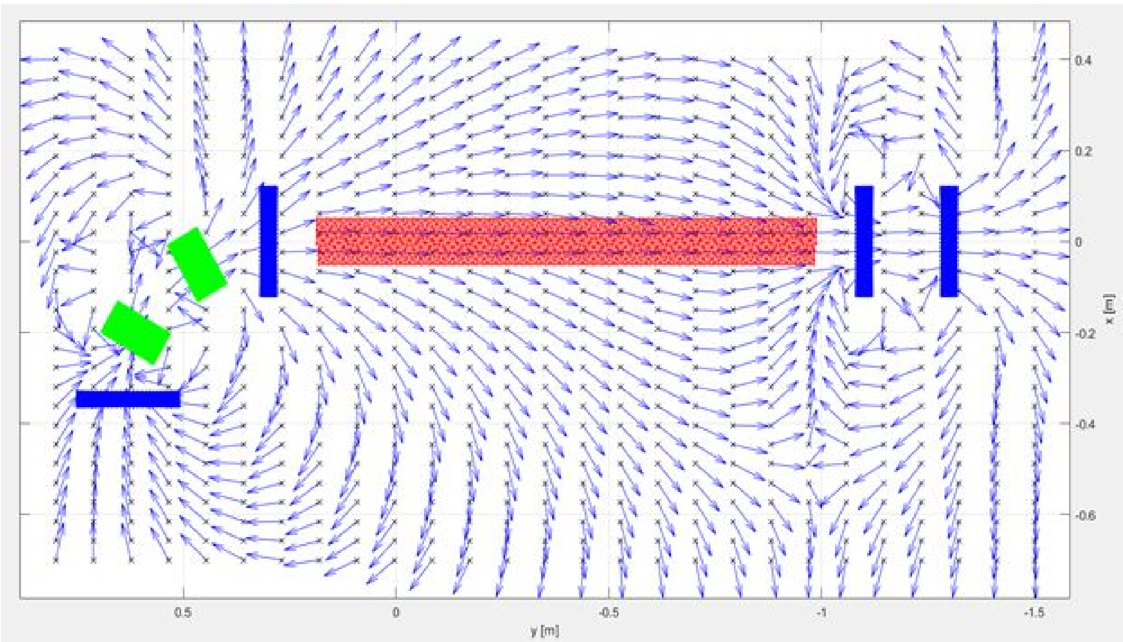

Figure 3.20*: Top view of the model*

Coil A (in green) will be used for the bellows section. Coil B (in blue) will be used around the containment unit on the junctions where the tubes will be connected. Coil C (in red) is the coil around the main chamber to ensure that the positrons go inside the electrode and toward the annihilation zone. As can be seen in Figure 20, the magnetic field lines in the centre of the system all go straight. Therefore, the magnetic field produced will prevent the collimated positron beam from colliding with the walls of the tubes and will direct it straight to the accumulator and the annihilation zone.

The current required in the coils to generate a magnetic field of 100 Gauss is as follows:

Coil A will require 26.9 ± 0.1 A.

Coil B will require 12.6 ± 0.3 A.

Coil C will require 5.75 ± 0.1 A.

3.7 Radiation Shield and Table

The following will show the design of the radiation shielding and a stress analysis on the table where the shield and containment unit will be placed. A stress analysis was done because we knew the shield would be very heavy as the entire thing will be 5349.19 kg as stated in the mass budget, Section 4.1. It should be noted that the shielding never came in from MarShield due to the global pandemic.

The table/shield design process is a complex one, mostly based on details concerning ergonomics, design, material properties, and structure. This study aims to analyze the shield design behaviour on the table by observing the interaction of forces between the table and the shield during the experiment. The main physical materials and mechanical characteristics of the table and shield were both taken into consideration. The FEM analysis study will show if the table is strong enough to bear the heavy mass of pure lead. The FEM analysis will be seen shortly in Figure 3.26 and Figure 3.27.

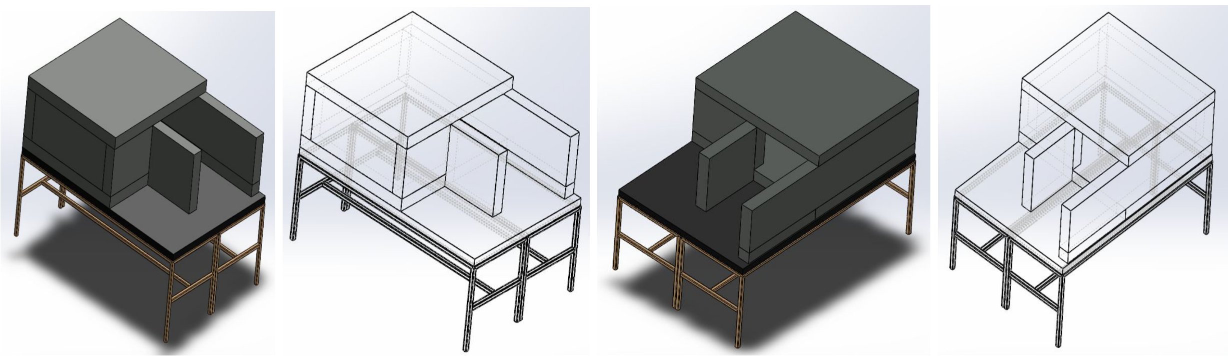

***Figure 3.21**: Shield Design*

Scope of analysis :

1. Study of present table/ brick specifications
2. Identification and problem finding
3. Collection of input/outputs data from analysis
4. Study of stresses, deformations of shields on the table

Methodology 2:

1. Study of present table/ brick specifications
2. Taken practical input from industry (MarsShield sponsor)
3. Analytical Analysis
4. Modeling via SolidWorks
5. Optimization of shield/table design

Building the Finite Element Model Using SolidWorks

The current design is concerned of the fact that the table will not be able to support the entire weight of the containment unit and the radiation shielding. An FEM analysis showing the weight distribution of the system on the table was done. The study precisely indicates the contact areas and distribution of forces while also demonstrating the shield pressure/force distributions for a wide range of areas on the table, as shown in Figure 3.25. The results are interpreted as equivalent resistance (von Mises stress), representing $\frac{N}{m^2}$. It is an indicator of good behaviour of the loaded model, if the maximum values are not reached.

Study of Present table/ brick specifications

The team is using three lab tables in Petrie Science Building in lab 118. The type of material for the first two long tables is Balsa wood, which is heavy solid wood with a yield strength of $2.0E + 07\frac{N}{m^2}$ **.** The third table is made of Carbon steel, which has high toughness and high strength, but it is not strong for its weight. Carbon steel has a yield strength of $283E + 08\frac{N}{m^2}$ **.** See Figure 3.22 and FIgure 3.23.

Property	Value	Units
Elastic Modulus	2999999232	N/m^2
Poisson's Ratio	0.29	N/A
Shear Modulus	299999910.5	N/m^2
Mass Density	159.989899	kg/m^3
Tensile Strength		N/m^2
Compressive Strength		N/m^2
Yield Strength	19999972	N/m^2
Thermal Expansion Coefficient		/K

Property	Value	Units
Elastic Modulus	2.049999984e+11	N/m^2
Poisson's Ratio	0.29	N/A
Tensile Strength	425000003.2	N/m^2
Yield Strength	282685049	N/m^2
Tangent Modulus		N/m^2
Thermal Expansion Coefficient	1.2e-05	/K
Mass Density	7858.000032	kg/m^3
Hardening Factor	0.85	N/A

***Figure 3.22**: Balsa Wood Property*

***Figure 3.23**: Carbon Steel Property*

***Figure 3.24:** Tables 1 (left) and 2 (middle) and the shield brick (right)*

The project required the use of lead bricks, so it was necessary to protect the users while the experiment was going on. The brick consists of **99.94%** minimum pure virgin high quality lead, and each single brick has a mass of **38 pounds**. The bricks would cover most of the first two tables, while the third table would support the rest of the equipment, as seen in figure (3.32). In this case, the bricks would be considered as a heavy mass and would create issues to continue the experiment. The two tables have a mass of **60 pounds** together and the whole shield on these two tables is **11168.16 pounds**. This mass is considerably high to be supported by Balsa wood. The experiment needed **294** bricks to cover the equipment on the table. Furthermore, the team has estimated that the force on the tables which is $49644.7632\ N$. The dimensions of the tables in Figure 3.24 are 121cm x 183cm for table 1. The dimensions of table 2 is 61.5cm x 91cm. Table 1 in Figure 3.24 will hold the radiation shielding while table 2 will hold the extending piece of the containment unit and is where annihilation will happen.

Calculations: <u>*inputs have been obtained via SolidWorks simulation*</u>.

How many bricks = $\frac{Bricks\ total\ mass\ over\ the\ table}{mass\ of\ one\ brick} = \frac{11168.16\ lb}{38\ lb} = 294\ bricks\ in\ total$

Total force on the two tables =

$Bricks\ total\ mass\ over\ the\ table * Gravity = 5065.7921629\ kg * 9.8\frac{m}{s^2} = 49644.76\ N$

SolidWorks will use these **outputs** and illustrate how the design would look like. With that the users would be able to study the stresses and deformations of shields on the table to identify any issue related to the design.

Stress Analysis:

The procedure for stress analysis is to build the FE model, define the material properties, such as young's modulus and density, apply boundary conditions and pressures, and then run the study and observe the results.

The maximum stress occurs when the lead shields and the experiment equipment are placed on the table. In case of high load of mass, we need to apply the von Mises stress to predict the yielding of materials under complex loading from the results of uniaxial tensile tests. The shield structure material is safe if the maximum value of the distortion energy per unit volume remains smaller than the distortion energy per unit volume required to cause yield in a tensile test of the specified material. This is considered an appropriate method to find out if the tables can handle this high load of lead bricks.

Applying $4.96 \times 10^4\ N$ **force on an area of** $2.21\ m^2$ **(force is applied on the first two tables)**

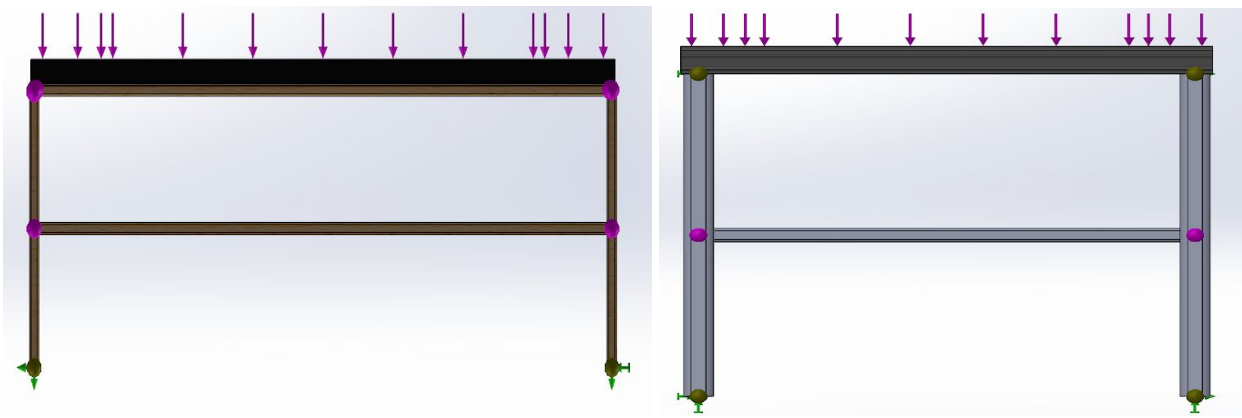

***Figure 3.25**: Weight distribution on table*

After we applied the force on the two tables, we observed high von Mises stress in some spots and higher than yield strength.

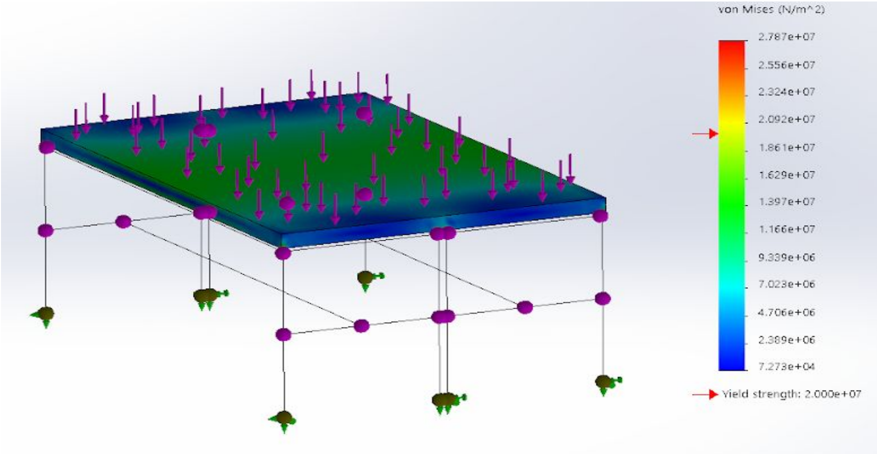

***Figure 3.26**: Von mises stress plot*

The results of the von mises were proven correct by showing that the rate of stress occurs more in the edges/middle of the table, and this is considered a weak spot on the table. Moreover, the huge mass of the lead shield will make the table unsafe to be used for the experimental purpose. Comparing the von Mises stress with the yield strength, would give us close values to the yield strength of the table material. This means that the table might deform or bend in some spots like in the middle, Figure 3.27. The maximum deformations induced on the table due to the force is **0.06 m**, which is unsafe. As well, the yield strength determines the safety factor until the start of deformation.

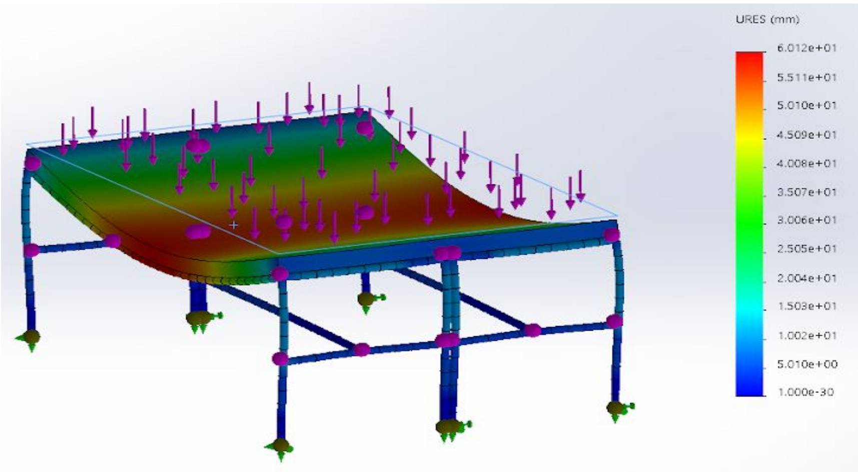

***Figure 3.27**: Displacement plot*

There is very high displacement in the middle of the table. Therefore, the deformation would occur in the middle of the table. The higher the percentage of the bending phase, the greater the deformation.

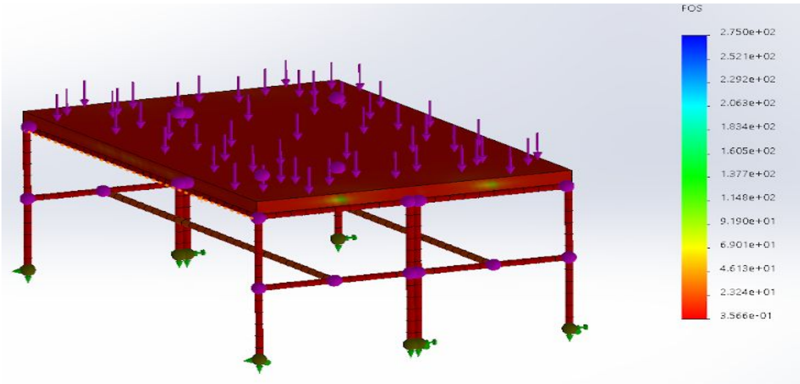

Figure 3.28: The Factor of Safety (FOS)

The factor of safety increases the safety for people and reduces the risk of failure of a product. When it comes to safety equipment and fall protection, the factor of safety is extremely important. If a structure fails, there is a risk of injury and financial loss. The safety factor is higher when there is a possibility that a failure will result in such circumstances. Figure 3.28 shows there would be an obvious failure in the table design while supporting the shields.

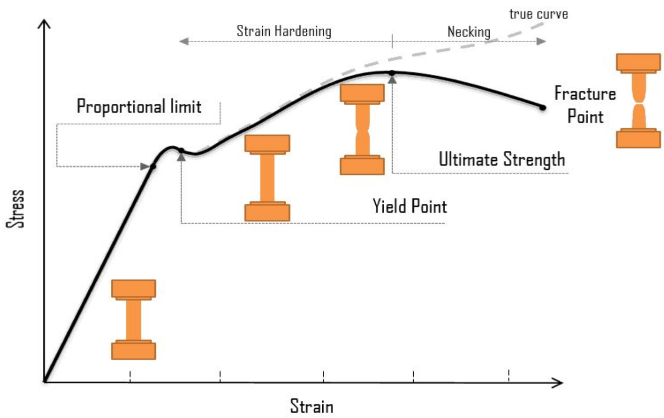

***Figure 3.29:** Stress-strain graph*

Following the stress-strain Figure 3.29, the fracture point case occurs during the experiment. As seen in Figure 3.26, Von Mises stress passes or is close to the yield strength point. Taking into consideration the huge mass, the shield will be on the table for a long time during the experiment. So, it might bear for a limited time. Therefore, there will be a big chance that the table will bend.

Moreover, the table having lateral deformation behaves under load, reaching high values of displacement, Figure 3.27. Only a small area shows bending, at the corners and by the joint of the table, but they are not critical.

When loading the table, users noticed higher tensions/stress in the legs, with reaching critical values, Figure 3.27 and Figure 3.26. Also, at the joint the users see higher values but again they do not reach the maximum.

Shield design

In the design of a protective shielding system, one of the key considerations is preventing the penetration of the rays. As stated earlier, the property of the shield material of the most significance in preventing this penetration is its density. Lead enjoys the advantage of being the most dense of any commonly available material. It is recognized that lead is not the most dense element (i.e., tantalum, tungsten, and thorium are higher on the density scale), but lead is readily available, easily fabricated and the lowest cost of the higher density materials.

Lead bricks are also more resistant to damage than, e.g., concrete. The unique design of the interlocking type permits mating surfaces to interlock, Figure 3.30, thus preventing the leakage of radiation. Any rays that penetrate the first angle of the interlocking joint will strike an equal or greater depth of lead than the straight thickness of the wall. Lead bricks are manufactured to extremely accurate tolerances, and as a result of recent production improvements, can be obtained with the almost complete absence of porosity. The smooth surfaces of lead bricks allow for easier decontamination of the shield from radioactive dust.

In solidworks simulation, the users have used the block bricks to show how the design would look like. But in reality, the users would use a v-shaped interlocking brick. Taking in consideration to use the same thickness and dimensions

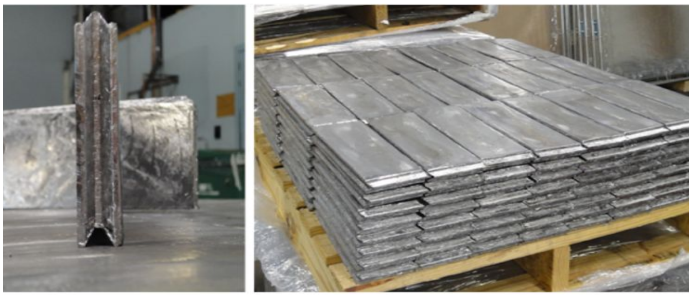

Figure 3.30: *The lead bricks that will be used*

Reducing the risk of radioactive exposure is done by placing the source in the farthest point inside the shield cave design. **Four-inch thickness** of lead is suitable enough to prevent the gamma ray's penetration. The users will face an insignificant rate of gamma rays as there is hole from the cave design, therefore, the designers decided to build extra shields along the equipment. The idea behind that is letting the rays lose their energy inside the cave and the insignificant rays leaving the cave will hit the extra shield from the right side (red line) and then the reflected rays would hit the other left side (green line) of the shield to eliminate the rays, Figure 3.31. Gamma rays will keep reflecting forwards and backwards inside the cave till they lose most of their energy or to be eliminated. This methodology will reduce the risk of gamma ray's exposure.

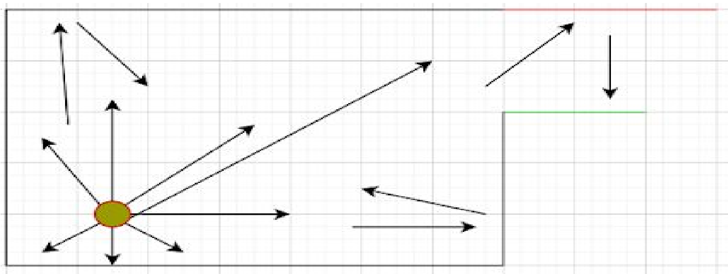

***Figure 3.31**: Gamma rays' directions*

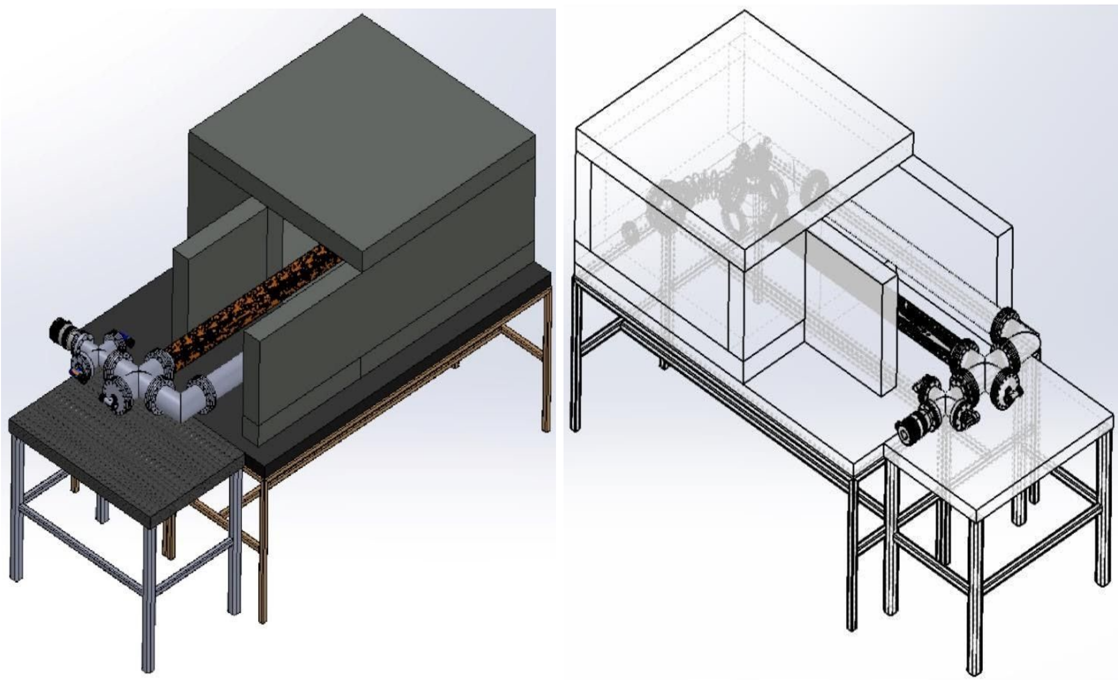

***Figure 3.32**: Shield design and the equipment on the table*

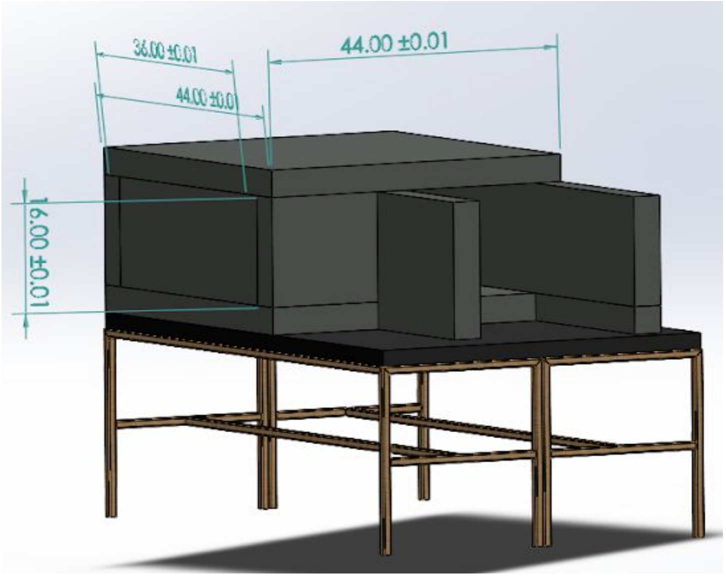

***Figure 3.33**: Shield design dimensions*

The empty space inside the cave would have a height of **16 inch** and width of **36 inch**. Based on the equipment dimensions, the users applied these dimensions to place the equipment inside the cave. To be on the safe side, the designers made a space between the walls and the equipment as seen in Figure 3.33. To protect the equipment and to be ready in case of vacuum chamber failure. This space would help to remove the shields easily and fix the issue related to the equipment. And then the user can return the shield on the right spot after the issue has been resolved. Meanwhile, the users need to take in consideration the source activity in case of removing one of the bricks.

3.8 Detection System

The purpose of the detection system is to record and detect the positrons by analysing gamma rays that are given off due to the annihilation of the positrons. Once the positron reaches the end of the vacuum tube it will proceed to collide with the inner walls and cause the radiation to disperse perpendicularly towards the PMT. The output of the photomultiplier tube is directly connected to the MCP3008 analog to digital converter, which then feeds the data into the raspberry pi. The following figures give an overview of the photomultiplier tube functionality.

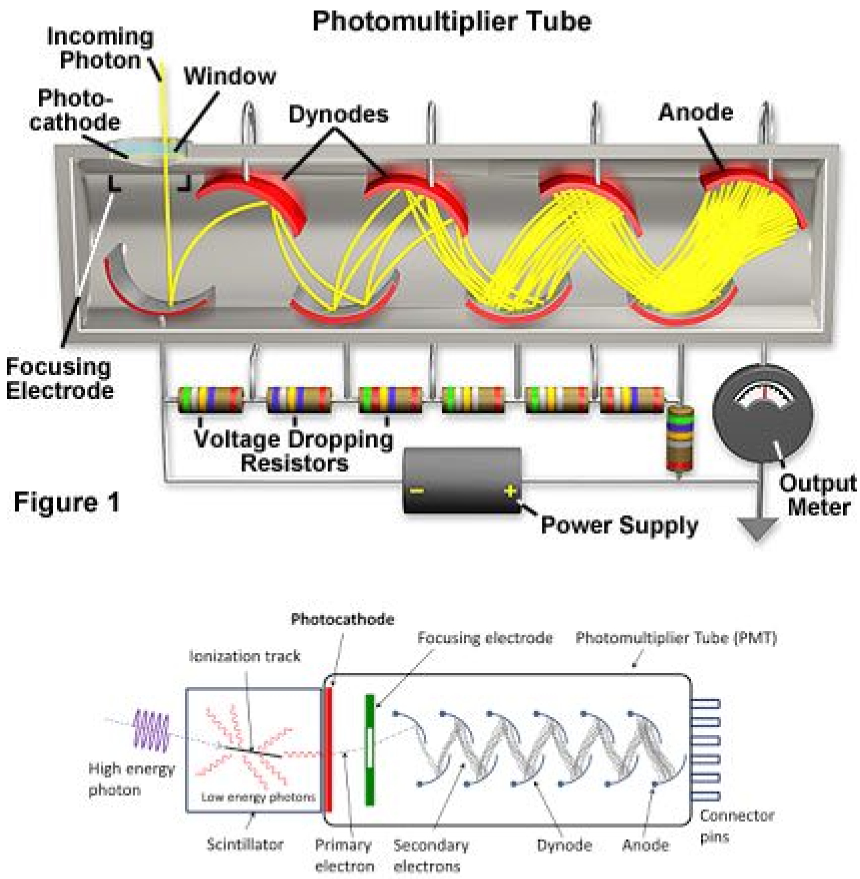

***Figure 3.34**: Photomultiplier tube functionality*

The data from the photomultiplier tube is constantly fed into the raspberry pi at a rate of 100,000 samples per second. To ensure that the raspberry pi can retrieve this data fast enough, the code had to be developed carefully to be as efficient as possible. This was done by pushing incoming raw data to a queue, and having a separate process work on retrieving the raw data from the queue and converting it into voltage values. This way, if data comes in faster than can be processed, the queue builds up but never loses any data, and the Raspberry Pi can process items in the queue at its own rate. As items are processed, they are written to a comma separated value file with a timestamp (also done in a separate process to ensure the incoming data always makes it into the queue). The end result is a time series of the photomultiplier signal which can be used to determine when annihilations occured. The area under the spikes seen in this time series represents the quantity of positrons that annihilated, allowing us to estimate how many positrons were contained. The following figures show the data acquisition code that runs on the raspberry pi, which reads the photomultiplier tube data from the analog to digital converter.

```python
import spidev
import io
import time
import datetime
import signal
import sys

t0 = time.time()
stream = []

out = io.FileIO("daq" + datetime.datetime.now().strftime("%d-%m-%Y_%H-%M") + ".csv", 'w') #create output file with date as name
writer = io.BufferedWriter(out, buffer_size=10000000) #set buffer size to 10Mb
writer.write(str.encode("daq value,timestamp\n"))

def main():
    #Create SPI
    spi = spidev.SpiDev()
    spi.open(0, 0)
    spi.max_speed_hz = 5000
    spi.mode = 0b00

    _t = time.time()
    while time.time() - _t < 1:
        spi.xfer2([1, 8 << 4, 0])

    t0 = time.time()
    while True:
        stream.append(spi.xfer2([1, 8 << 4, 0]))
        time.sleep(1/5000)

def flushStream(dt, size):
    l = len(stream)
    t = [str(((stream[i][1] & 3) << 8) + stream[i][2])  + "," + str((dt*i) / size) + '\n' for i in range(l)]
    s = ''.join(t)

    return s

def exit(sig, frame):
    t = time.time()
    dt = t - t0
    size = len(stream)
    freq = size / dt

    writer.write(str.encode(flushStream(dt, size)))
    writer.flush()

    print("stopping")
    print("finished in {} seconds, with {} samples, giving a sampling rate of {} samples per second.".format(dt, size, freq))
    sys.exit(0)

if __name__ == '__main__':
    signal.signal(signal.SIGINT, exit)
    main()
```

***Figure 3.35**: Data Acquisition Code*

3.9 Vacuum Emergency Stop Circuit

The main purpose of the circuit implementation shown below is to read pressure results along with the corresponding voltage value in conjunction with using python code via a relay circuit to monitor pressure readings. If the pressure would begin to gradually increase then the vacuum system must be turned off immediately as there must be some flaw in the system.

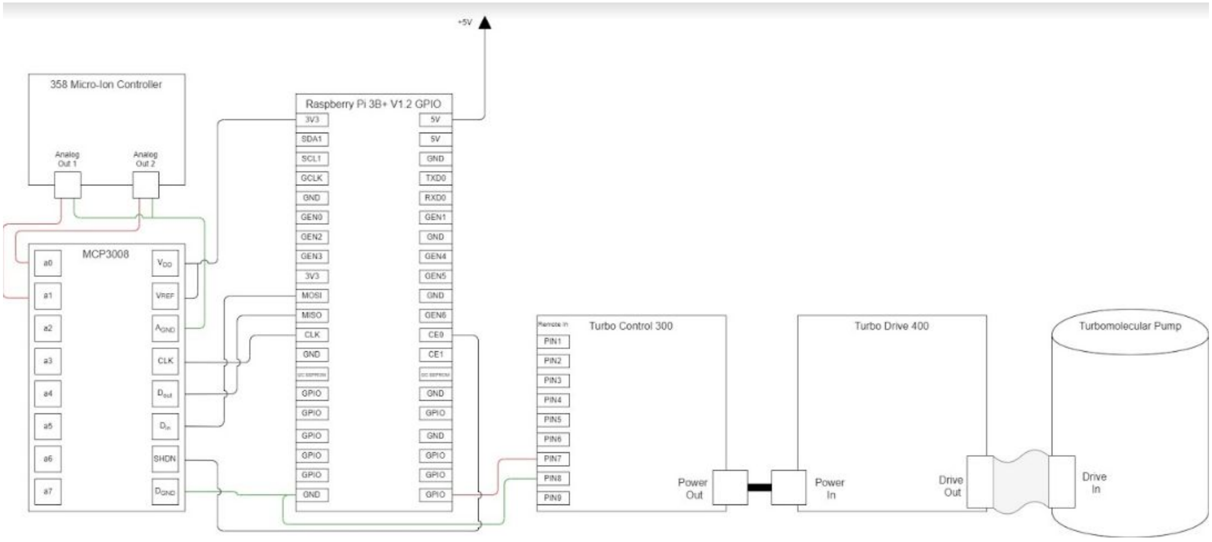

Figure 3.36: *Vacuum Emergency Stop Circuit*

As shown above, this is the implementation of the emergency stop circuit. The main control unit is the Turbo control 300. This unit is the operation source of the turbomolecular pump (this pump is the driving force to lower the pressure in the containment unit to 10^{-7} Torr) Now behind all this is the logic design of the circuit. The ADC (analog to Digital Converter) which is the MCP3008 microchip reads in pressure values, as well as voltages from the 358 Micro-ion Controller. Based on these values, the raspberry pi would toggle the Turbo Control 300 to turn on the Turbomolecular pump once the Pressure reached a value of about $4x10^{-1}$ Torr.

The emergency stop circuit is constantly reading data from various pressure gauges to determine if the change in pressure of the system is going to reach a condition where some equipment may be damaged. If these conditions are met, then the emergency stop circuit sends a signal to the different pump controllers to toggle them. The following chart shows the various cases for which the emergency stop circuit will trigger.

***Table 3.5**: Triggering Events for Emergency Stop Circuit*

Triggering Event(s)	Device(s) Affected	Initial Status	Post Toggle Status
1.) System Operation Signal Sent	Atmospheric Pump Controller	OFF	ON
2.) System Halt Signal Sent	Turbomolecular Pump Controller	ON / OFF	OFF
	Atmospheric Pump Controller	ON / OFF	OFF
3.) Vacuum Pressure is Decreasing AND Vacuum Pressure is <=0.075 torr	Turbomolecular Pump Controller	OFF	ON
	Atmospheric Pump Controller	ON	OFF
4.) Turbomolecular Pump is on AND Pressure is increasing AND pressure is >= 0.05 torr	Turbomolecular Pump Controller	ON	OFF
	Atmospheric Pump Controller	OFF	ON

Many of the above conditions are not actually emergency cases; however, the stop circuit is also responsible for toggling the various pumps when necessary.

3.10 Limitations of the Overall Design

One of the limitations of this is that when nitrogen gas will be injected into the system, there will be a larger pressure gradient compared to a system if two turbomolecular pumps were available. The current design is restricted and bounded by a single turbomolecular pump. A second turbomolecular pump would allow the second long pipe to not be present, thus lowering the overall cost of what will need to be bought for the current design. The second pump would also allow a smaller pressure gradient to be present within the system. This would lower any possible anomalies that could occur within the system.

Another limitation is the length that the design was constrained to. One of the constraints of the design was that it had to fit on a certain sized table as previously explained. A longer pipe combined with two pumps would allow a more finely tuned pressure region to be attained. This would ultimately increase the overall efficiency of the trap.

Currently, a tungsten moderator is being used within the system. A solid neon moderator can be used to allow a larger amount of positrons to be moderated within the system. However, a solid neon moderator would be very expensive as one would have to cool the neon to almost absolute zero to attain that phase. The infrastructure and finances is not available at the physics department for that.

4 As-Built Design Compliance Analysis

4.1 Mass Budget

The mass budget was not originally created during the PDR. Upon ordering the radiation shielding, we had realized that the mass of the system might be more than the lab tables can support, which was unexpected. Thus, a mass budget has been created to determine the total mass of the system, allowing us to order more sturdy tables if required. Note that the ordering of these tables will depend on a distributed load analysis of the lab tables in the lab which this experiment is being setup in, this has already been done for the tables currently in the lab as can be seen by figure 6, but will need to be redone for different lab tables in the future.

The following table shows the mass budget for this project. This is a crucial budget since the system needs to be able to fit on lab tables so that the experiment can be easily conducted without the worry of the radiation shielding being interfered with. Therefore, the mass budget directly influences the type of tables that may need to be purchased for future implementations of this project.

Table 4.1: *Mass Budget*

Module	Nominal Mass (Kg)	5% Contingency (Kg)
Detection System	15	0.75
Vacuum System	224.40	22.44
Nitrogen Gas Injection System	20	1.0
Radiation Shielding	5065.79	253.29
Miscellaneous	24	2.4
Totals	5349.19	267.46

The heaviest module in this system is the radiation shielding. This is because the radiation shielding needs to be made out of lead to be able to stop the gamma radiation that is emitted by the radioactive source. Lead is a very heavy material, and since so much is required, most of the mass budget consists of the shielding.

The vacuum system is the second heaviest module in the system. This is because most of the component parts within the project lie within the vacuum system. These parts are mostly stainless steel tubes that are assembled together to make the various vacuum chambers that comprise the entire assembly. Although not as heavy as lead, stainless steel is still very heavy, and the mass of the vacuum system needs to be taken into account.

The least heaviest modules are the detection system and nitrogen gas injection system modules. The weights of these modules are so small relative to the others because comparatively, these modules do not have as many components. The weights of these components also do not affect decisions made on mass supports since they can be stationed further away from the system, and in the case of the detection system, can mostly be located on a separate table interly, if necessary.

The final section of the mass budget considers miscellaneous items. These items are crucial to the development of the project, but do not directly fit into the other modules. One example of these items are the various coils that are placed around the vacuum system that steer the positrons.

4.2 Power Budget

The following table shows the power budget for this project. It is broken into the only two modules that draw significant amounts of power, the detection system and the vacuum system. It also includes miscellaneous power draw from items that do not fit into either module, but still require power. Each module runs off a laboratory power rail that can supply 120 Volts and up to 15 Amps. This means that the maximum power draw for any module cannot exceed 1,800 Watts, or else it will require power from more than one power rail. Since each lab in the Petrie building only has a limited amount of power rails, it is desirable to have each module only use one to minimize the amount of rails required for the project. This power budget has been expanded on since the PDR, and now shows the power draw of the various modules in much more detail.

***Table 4.2**: Power Budget*

Module	Nominal Power Draw (W)	10% Contingency (W)
Detection System	211.25	21.13
Vacuum System	170	17
Magnetic Fields	291.16	29.12
Miscellaneous	8	0.8
Totals	680.41	68.04

The magnetic fields required to guide the positrons at various locations of the system are very strong. Thus, they are the component of this project which draws the most amount of power. This is mostly because so many coils are required at many different locations of the system.

The detection system module is the module which consumes the second most power. This is because the photomultiplier tubes which are used to detect the positron annihilations require large amounts of power to operate. On top of this, the raspberry pi which is used to measure the output signals from the photomultiplier tube also requires power, but a much smaller amount. Depending on the detection setup, there may be a desire to use a discriminator and a rate meter to alleviate some of the software computations. Both of these require a special power supply to operate, causing the power draw for the module to increase even further.

The vacuum system module is another module which requires a lot of power. The power requirements for the vacuum system stem from the two pumps, and the emergency stopping mechanism. The turbomolecular pump allows the system to achieve a high vacuum status, but it requires a lot of power when it is operating. The roughing pump also requires a bit of power to operate, but not as much as the turbomolecular pump. Relative to the two pumps, the stopping mechanism's power draw is miniscule, but it still needs to be considered.

The last section of the power budget is the miscellaneous components. These are things such as laboratory computers, or oscilloscopes that are required to analyze the data received from the experiment. The power draw of these is dependent on the specific lab setup used for the 4th year physics lab, but the budgets have been computed for an assumed setup of 1 computer, and 1 oscilloscope.

4.3 Computational Resource Budget

There is only one item that concerns computational resources in this project. The driving computer (Raspberry Pi) needs to be able to read and perform basic parsing operations on the data as it is fed directly from the photomultiplier tubes. The data comes in at a rate of 100,000 samples per second. Each sample contains 10 bits of information, which is received from a 10 bit analog to digital converted. This means that the Raspberry pi must be able to process 125 kb/s of information. The computational resources required for this project are so miniscule, that contingency does not need to be considered. For reference, the USB 2.0 interface that allows the Raspberry Pi to read this data has a maximum throughput of 60 Mb/s, meaning that the operation of the experiment only consumes approximately 0.21% of the total data bandwidth.

4.4 Memory Budget

The memory budget for this project is also fairly simple. Each experiment is set to collect data for 10 seconds, with a timestamp collected for each sample. The data is then saved as a comma separated value (.csv) file. Thus, the total memory usage for one run of the experiment can be computed easily. The timestamp size is 4 bytes, or 32 bits, each sample contains 10 bits of data, and each comma character used to separate the data is 1 byte, or 8 at bits. This means that for each sample, 50 bits of data are being stored. Thus, for a 10 second execution of 100,000 samples per second, a total of 50,000,000 bits are stored on the raspberry pi. This equates to 6.25 Mb of data, which is very small. Thus, the memory allocation required for this project is so miniscule that contingency does not need to be considered. For reference, the micro SD card used in the Raspberry Pi for this project is 32 GB, meaning that each execution only uses approximately 0.02% of the available memory.

4.5 New Non-Conformances

Due to the global pandemic, no tests have been able to be conducted since the completion of the test review. As such, there have been no new non conformances that have been reported. When the project continues, and the tests are performed, future non conformances will continue to be reported using the google forms tool. This tool can be accessed at the following link.

https://docs.google.com/forms/d/e/1FAIpQLSdIk9vZ8Q3AqUtXLaG9WUnzpLx6v9V9t-XN0PM7iodg5nle-w/viewform?usp=sf_link

5 As-Built Work Breakdown Structure

The full antimatter containment unit work breakdown structure is available from the following link.

https://drive.google.com/file/d/153G_6dXuZIQrdDQzJodWHVINjyJCRcu2/view?usp=sharing

The top level of the work breakdown structure for this project splits into the five main sections of the project, design, assembly, testing, data collection, and lab development. The following figure shows the top two levels of the breakdown structure.

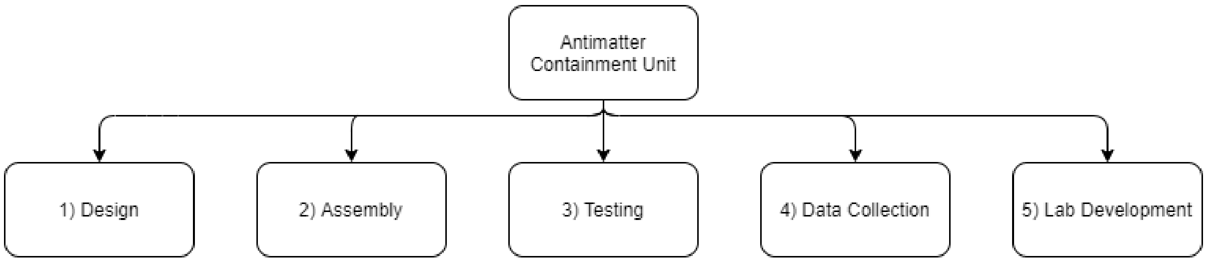

Figure 5.1: *Top level work breakdown structure*

These five main sections of the project each contain their own various subsections which all eventually lead to the work packages of this project. The following figures show the work breakdown hierarchy of each of these main sections. There are four colours used to represent the status of the lowest level work packages. Green work packages indicate packages that have been completed. Blue work packages indicate packages that have been added since the PDR; all of which have also been completed. Yellow work packages are items that are currently in progress, or have been paused due to changes in the project requirements. Red work packages have not been completed, or have a very small amount of work done on them. Although a large section of this project was unable to be completed due to unforeseen circumstances, many of the team members are well invested in the project, and are eager to begin work again once the global situation permits.

5.1 Design Work Package Hierarchy

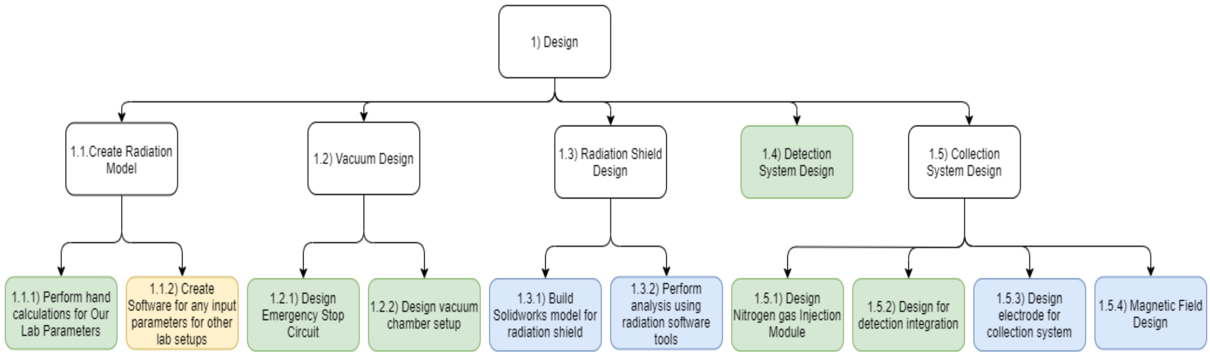

Figure 5.2: *Design work breakdown structure*

There were 4 major work packages that were added to the design section of the work breakdown structure since the PDR document. These work packages consist of the development and analysis of a radiation model, the design of an electrode, and the design of a magnetic field to guide the positrons. The additional work packages under the radiation shield design had been considered during the PDR phase; however, it was thought that they would not amount to enough to be considered work packages. Further analysis had the project team realize that these sections required sufficient amount of work, so separate work packages were created for the development of the model, and then the analysis of the model. The electrode design was added during the assembly phase of the project, as the team had realized the supplied electrode would have to be heavily modified to suit the experiment. Similarly to the new radiation shielding work packages, the design of the magnetic field was also considered in the PDR, but further work on the design of the system allowed the project team to realize that it warranted it's own work package in the WBS.

5.2 Assembly Work Package Hierarchy

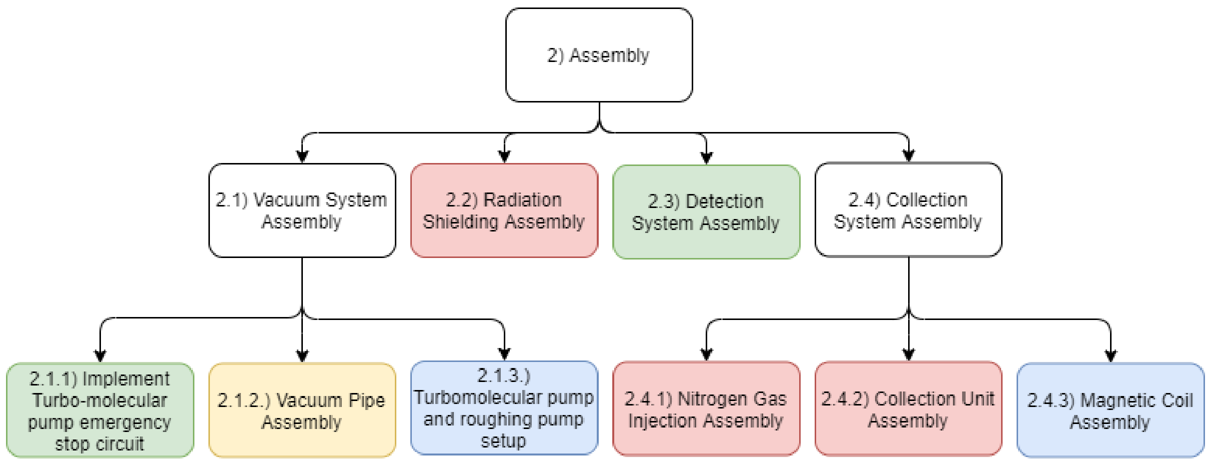

Figure 5.3: *Assembly work breakdown structure*

There were 2 work packages that were added to the assembly section of the work breakdown structure. Similar to some of the new work packages in the design section, these items had been planned originally, but the amount of work required for each constituted the creation of a new work package since the scope of these items increased. These new work packages are the vacuum pump setups, and the assembly of the magnetic coils. The assembly section also has some work packages that were not able to be fully complete due to the unexpected pandemic. These work packages include the radiation shielding assembly, the nitrogen gas injection module assembly, and the assembly of the positron collector.

5.3 Testing Work Package Hierarchy

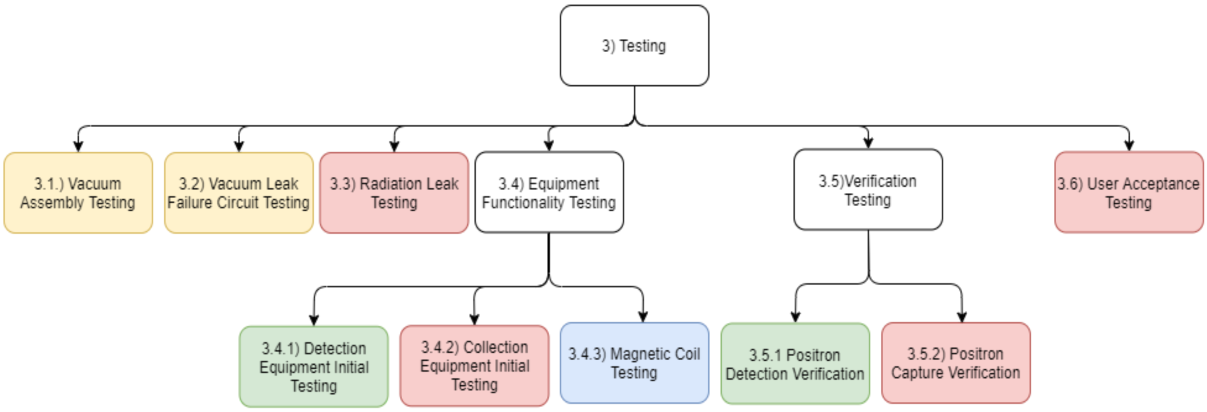

***Figure 5.4**: Testing work breakdown structure*

The testing section of the work breakdown structure only saw one additional work package. This work package fits in with the other additional work packages in the design and assembly section that dealt with the development of the magnetic coils. The testing section also has a few work packages that were not able to be complete. These tests were unable to be completed because they are dependent on the incomplete work packages in the assembly section. The incomplete work packages include the radiation leak testing, the initial collector testing, the positron capture verification testing, and the user acceptance testing.

5.4 Data Collection Work Package Hierarchy

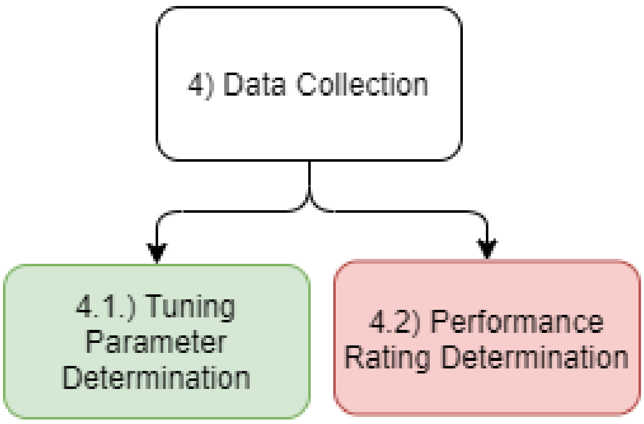

***Figure 5.5**: Data collection work breakdown structure*

The data collection section of this project was the smallest section and only had two work packages. Unfortunately, in order to rate the performance of the system, it needed to be finished in entirety, and rigorously tested.

5.5 Lab Development Work Package Hierarchy

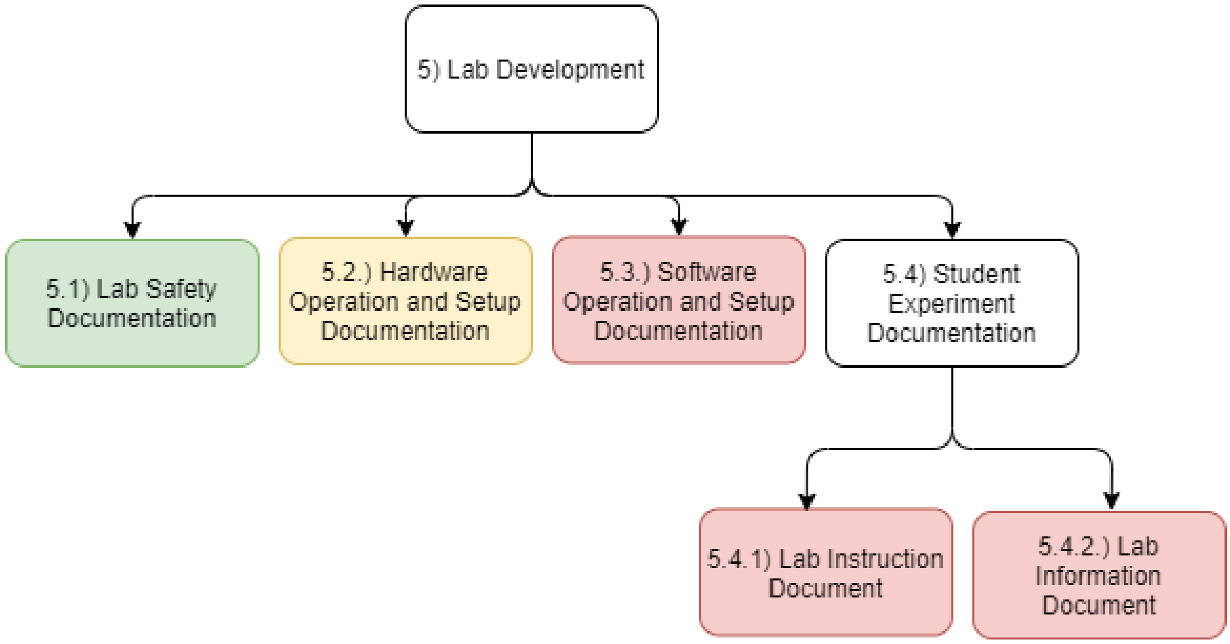

***Figure 5.6**: Lab development work breakdown structure*

The final section of the work breakdown structure is the lab development section. Since the experiment couldn't be completed, the lab was unable to be developed. Specifically, the software setup documentation, the lab instruction documentation, and lab information documentation are incomplete.

6 As-Built Work Package Descriptions

Appendix B outlines the work packages that were introduced in the previous section. Section 15.2.1 outlines the new work packages, outlined in blue above. Section 15.2.2 outlines work packages that had been modified during the course of the project. The final section, 15.2.3, summarizes the work packages that have not changed since the PDR.

6.1 Work Package Changes

As mentioned previously, the appendix in section 15.2.2 outlines work packages that were changed throughout the course of the project. These changes range from small things like changing the work package manager, or changing the amount of time dedicated to working on the work package. However, some changes were much larger and included changing the work package tasks to be undertaken, or even completely reworking the work package. This section will cover a few of the work packages that changed drastically, and provide insight on how to avoid some of the pitfalls that were encountered during the design phase that resulted in the need to drastically change the requirements.

DE-VD-2-4 - Vacuum Chamber and Pathway Design

This work package involved designing the vacuum module using the materials that were donated to us by the project sponsor. At the beginning of the project, our team believed we had many parts available to us, and so, we designed a vacuum system around these parts. As the project continued, it was realized that many of the parts that the team thought were in storages around the Petrie building, were not actually available. Due to this, a major change in the design was required. A stockpile had to be created to ensure that the parts we believe we had, were actually available, and orders needed to be created to ensure the parts that were not available could be acquired. On top of this, since parts needed to be ordered that were not expected, the required financial budget of the project grew dramatically. Our team needed to conduct fundraising activities to ensure that the project would not fail. Thankfully, after many additional hours of hard work, the project team was able to order all the required parts, and find sponsors to ensure the project had the budget to fulfil the orders.

This could have easily been avoided if the project team better performed due diligence at the beginning of the project and created a stockpile of all the available materials and parts. Even though the issue of missing parts would have still come up, it would have been before an initial design was created, thus not wasting valuable time. On top of this, discussions could have begun with potential sponsors earlier, and perhaps we would have been able to secure more sponsorships; however, this is just speculative.

DE-DSD-6 - Detection System Design

In contrast to the previously mentioned work package, this work package changed drastically due to an overall decrease in time required. This was mainly due to the fact that during development on the work package, the team realized that one of the required tasks was not necessary, as the design has slightly changed. Although this was beneficial, the design could have easily changed in such a way that required more work. Our team believes that this could have been avoided by ensuring that all members who work on a specific work package inspect it thoroughly during the development of the PDR. If this had happened, it would be likely that one of the team members would have caught the mistake, allowing the work package tasks to be created better.

TE-EFT-2-19 - Collection Equipment Initial Testing

Although this work package did not see changes to the tasks that were initially assigned, it did see a huge increase in the amount of work time that was expected. This issue stemmed from improper communications between the engineering and physics teams. The engineering team created the original work package description and tasks; however, these tasks were not fully understood at the time. Thus, the scope of the work package was improperly defined. A lot more resources were required for this work package that were unexpected. In the future, this could easily be avoided by ensuring that all teams give their feedback on the work packages that were defined. If a member of the physics team had reviewed this work package, it is likely that the mistake would have been noticed and corrected. As a result, the following work packages would have been better planned, allowing for a better distribution of resources across other areas of the project.

7 As-Built Resource Allocation Matrix

The resource allocation matrix below lists all work packages with their respective ID, and it allots the appropriate amount of time for each package towards the individual(s). The first three letters of the members of the group have been listed below and listed in the table. The green boxes represent the managers of the work package and the orange represents the supporters. The red represents that the individual has been removed from this work package due to a few possible reasons and the evolution of the demands and placement of the individuals' respective abilities. The dark green and dark orange represents any new managers and supporters that have been added since the PDR. The light blue represents new work packages that have been added. The number listed under each individual in Table 7.1 and Table 7.2 shows the number of hours that individual will work on the respective work package and in the month respectively. The number of hours worked for each month is a rough estimate and does not show actual hours worked.

Due to miscommunication with group members, the number of hours for each manager and supporter have been changed dramatically. For each work package, the managers must partake in the number of hours listed for that package and the supporters will do 50% of the listed hours required to complete the work package. For example, the work package DE-CRM-1-1 has a required input of 25 hours. Therefore, the managers of this work package will each do 25 hours and the supporters will do 12.5 hours. Following this, the total number of hours required for this project increases from 430 to 1530 with the addition of the new work packages added. This value makes a lot more sense due to the complex nature of the project. Note that some members from the C4 team will not be contributing towards the project until the winter semester.

Table 7.1 shows the number of hours each individual will work for each work package as outlined in the work packages in Appendix A. Table 7.2 shows a rough estimate of the number of hours that will be worked each month. Some of the work packages that took long were the packages that had 30 or 40 hours required for their completion such as DE-CSD-2-8.2 and AS-VSA-2-10.1. The reasons why these work packages can take so long is because some of these tasks can be very complex through many iterations and may require a lot of problem solving. For example, AS-VSA-2-10.1 required a small scale setup and testing of the roughing pump and turbomolecular pump to see if the desired pressures could be achieved. This small scale test required a lot of testing iterations to figure out why it wasn't reaching the desired pressure value.

However, due to the uncontrollable circumstances surrounding the COVID-19 pandemic, much of the project was forced to be incomplete in some areas. In Section 5, The As-Built Work Breakdown Structure, the red work packages are packages that haven't been started or have little work done upon them as previously explained. Adding up the number of hours in the red work packages, a value of 447.5 hours is achieved. That's roughly 447.5 more hours needed to complete the project once all the necessary components have arrived. The total hours of 1575 subtracted by 447.5 will give a value of 1127.5. This value is roughly the total number of hours worked on for this project. Once the situation around the pandemic clears up, this value will go up as some members of the team would still like to continue with the project.

It should be noted that this table doesn't account for all hours such as meetings, idea formulation, report writing and essential things like that.

Legend:
Green - Manger
Dark Green - Manager Addition
Orange - Supporter
Dark Orange - Supporter Addition
Red - Removal
Light Blue - Work Package Addition

Ash - Ashifa
Aks - Akshay
Hun - Hunter
Kar - Kareem
Moh - Mohammad
Yas - Yaseen
Amm - Ammara
Far - Farshad
Pru - Pruthvi

***Table 7.1**: Resource Allocation Matrix - Number of Hours by Work Package*

Work Package ID	Ash	Aks	Hun	Kar	Moh	Yas	Amm	Far	Pru	**# of Hours per manager**
DE-RSD-5.1	-	-	-	-	12.5	25	-	-	-	25
DE-RSD-5.2	-	12.5	-	-	-	25	-	12.5	-	25
DE-CSD-2-8.1	-	40	-	-	20	-	-	-	-	40
DE-CSD-2-8.2	-	-	-	-	-	-	40	-	20	40
AS-VSA-2-10.1	30	15	30	30	-	-	-	-	-	30

AS-CSA-2-14.1	-	-	-	-	-	-	30	-	15	30
TE-EFT-2-19.1	-	-	-	-	-	-	20	-	10	20
DE-CRM-1-1	-	-	-	12.5	25	25	-	-	-	25
DE-CRM-2-2	20	20	40	-	-	-	-	-	-	40
DE-VD-1-3	-	-	10	5	-	-	-	-	-	10
DE-VD-2-4	-	40	-	-	20	-	-	-	20	40
DE-DSD-6	-	-	10	20	-	-	-	-	-	10
DE-CSD-1-7	-	30	15	-	15	-	-	-	30	30
DE-CSD-2-8	-	5	-	-	10	-	-	-	-	10
AS-VSA-1-9	7.5	-	15	15	7.5	-	-	-	-	15
AS-VSA-2-10	7.5	15	7.5	-	-	15	-	-	-	15
AS-RSA-2-11	10	-	-	-	5	10	-	-	-	10
AS-DSA-12	-	-	10	20	-	-	-	20	-	20
AS-CSA-1-13	-	10	10	20	-	-	-	-	20	20
AS-CSA-2-14	-	20	20	10	-	-	-	-	10	20
TE-VAT-15	10	20	20	10	-	-	-	-	-	20
TE-VLFCT-16	2.5	-	5	5	2.5	-	-	-	-	5
TE-RLT-17	5	5	5	5	5	5	-	-	-	5
TE-EFT-1-18	5	-	10	5	-	-	-	5	-	10
TE-EFT-2-19	-	-	20	20	40	40	-	-	-	40
TE-VT-1-20	-	15	7.5	-	-	-	-	-	15	15
TE-VT-2-21	-	7.5	15	-	-	-	7.5	15	-	15
TE-UAT-22	10	-	-	10	-	-	5	10	5	10
DC-TPD-23	5	-	10	-	10	-	-	-	5	10
DC-PRD-24	5	2.5	-	-	-	-	5	-	-	5
LD-LDS-25	10	-	5	-	-	-	-	10	-	10
LD-HOSD-26	10	-	10	5	-	-	-	-	-	10

LD-SOSD-27	5	-	10	-	-	-	-	-	-	10
LD-SED-1-28	-	5	-	-	-	-	10	5	-	10
LD-SED-2-29	-	5	-	-	-	-	10	5	-	10
TOTAL	142.5	267.5	285	192.5	182.5	145	127.5	82.5	150	1575

Table 7.2: Resource Allocation Matrix - Number of Hours by Month

Month	Ash	Aks	Hun	Kar	Moh	Yas	Amm	Far	Pru	**TOTAL**
November	20	40	40	25	20	20	-	-	30	-
December	20	45	35	25	40	20	-	-	25	-
January	25	45	45	30	25	20	10	10	30	-
February	25	50	50	40	30	25	20	20	25	-
March	30	45	50	40	32.5	30	40	40	20	-
April	22.5	45	50	30	30	30	40	40	20	-
TOTAL	142.5	270	270	190	182.5	145	110	110	150	1180

8 As-Built Project Schedule

The following is a link to the project Gantt chart. Also note that at index E4 of the Gantt chart is the week selector. Change this value to change the start of the week of the current view.
Gantt Chart.xlsx

Given the unforeseen circumstances surrounding COVID-19, many of the end dates in the Gantt chart from the PDR were not met (some dates have been modified). As such, some of the work packages were modified and new ones were added and have been described in this report. The team has pushed some end dates further with the hope that the quarantine will be over in the next few months. Some requirements have been postponed due to COVID-19 like radiation shield assembly, vacuum assembly, collection system assembly. Many of the team members are interested in coming back to finish the project if the future situation allows that to happen.

9 As-Built Project Procurement/Equipment/Travel List

As it currently stands, the project procurement list consists of 3 categories. The first is the equipment that we have purchased. The second is the equipment that was donated and/or borrowed from either the Physics Department at York University or external sponsors that were donating product(s) to support the project. Finally there is equipment that needs to be purchased in order to complete building/assembly and begin testing.

In the beginning, it was originally thought that all necessary equipment was possessed by the physics department. Excluding some minor electrical equipment such as SD cards, the major thing required to be bought was lead shielding. Table 9.1 was constructed listing all the current parts in inventory supplied by the Physics Department that we will be using in the construction of the containment unit. It should be noted that all prices in this section are without tax.

However, the donated equipment from the physics department was not sufficient and this came to light around mid- January when building was begun. The “As-Built Design” as shown in section 3.1 is the summation of the extent the project could’ve gone in the building process from the equipment on hand (see Table 9.1 below). In order to go beyond this stage, a way to fund the acquisition of the rest of the equipment was needed to be found. It is at this point that the option of obtaining sponsors was looked upon and discussed amongst each other. These sponsors were sourced from areas of industry where this project may have a direct business influence including York University and the related stakeholders within. For internal sponsors, light was shed upon the project’s impact upon success for the Lassonde School of Engineering, the Physics Department and the Faculty of Science. The C4 network was the driving force in helping the team get connected with the above internal stakeholders within York University.

Table 9.1: Summary table listing current inventory

Part #	Part Name	Qty	Source	Supplied?	Actual Cost
1	4-Way 6 in. Cross	1	Physics Dept	Yes	$0.00
2	3-Way 2 ¾ in. Tee	1	Physics Dept	Yes	$0.00
3	6-Way 3 ⅜ in. Cross	1	Physics Dept	Yes	$0.00
4	Bellow 4.5 in., L = 6 ⅜	1	Physics Dept	Yes	$0.00
5	Electrode 2 ⅛, L = 21 in.	1	Physics Dept	Yes	$0.00
6	Solenoid Nipple OD 6 in., ID 4 in., L = 48 in.	2	Physics Dept	Yes	$0.00
7	Moderator Extendor	1	Physics Dept	Yes	$0.00
8	Blank 2 ¾ in.	1	Physics Dept	Yes	$0.00
9	Blank 4 ½ in.	2	Physics Dept	Yes	$0.00
10	Blank 6 in.	1	Physics Dept	Yes	$0.00
11	Reducer (Zero Length) 4 ½ in. - 2 ¾ in.	2	Physics Dept	Yes	$0.00

12	Reducer (Zero Length) 3 ¼ in. - 2 ¾ in.	1	Physics Dept	Yes	$0.00
13	Reducer (Zero Length) 6 in. - 4 ½ in.	1	Physics Dept	Yes	$0.00
15	Reducer (Zero Length) 6 in. 2 ¾ in.	3	Physics Dept	Yes	$0.00
16	Turbomolecular Pump	1	Physics Dept	Yes	$0.00
17	Roughing Pump	1	Physics Dept	Yes	$0.00
18	Photomultiplier Tube	2	Physics Dept	Yes	$0.00
19	Power supply - Moderator	1	Physics Dept	Yes	$0.00
20	Power supply - Cleaner	1	Physics Dept	Yes	$0.00
21	Power supply - Electrodes	1	Physics Dept	Yes	$0.00
22	Power supply - Pumps	1	Physics Dept	Yes	$0.00
23	Power supply - Solenoids	1	Physics Dept	Yes	$0.00
24	Ratemeter	1	Physics Dept	Yes	$0.00

25	Discriminator	1	Physics Dept	Yes	$0.00
26	Raspberry PI 2 B+	1	Personal Item	Yes	$0.00
27	Nitrogen Gas	N/A	Physics Dept	Yes	$0.00
28	Gas Injection System	1	Physics Dept	Yes	$0.00
29	Sodium 22	N/A	Physics Dept	Yes	$0.00
30	O-Rings	N/A	Physics Dept	Yes	$0.00
31	Nuts	N/A	Physics Dept	Yes	$0.00
32	Washers	N/A	Physics Dept	Yes	$0.00
33	Bolts	N/A	Physics Dept	Yes	$0.00

Table 9.2 below shows the estimated value of the donated equipment we will be using in the antimatter containment unit assembly. This was all donated and given for free.

***Table 9.2**: Estimated value of the donated equipment by the Physics Department at York University*

Equipment	Price ($CAD)
Turbomolecular Pump and accessories	10,000.00
Photomultiplier Tube and accessories	3,000.00
Roughing Pump and accessories	300.00

Vacuum pipes/connections/accessories + solenoids and electromagnets	8,000.00
Na-22 1 Microcurie test source	100.00
Na-22 5 Millicurie experiment source	N/A
Total	**21,400.00+**

Table 9.3 lists all the purchases that were made throughout the year from the $1000 budget given in the project. All the purchases were related towards the software and electrical components of the project.

***Table 9.3**: Summary table of all expenses*

Receipt	Expense Description	Total in CAD(Including HST)
A2.1	SD Card	$21.46
A2.2	Energizer Battery	$23.72
A2.3	NOYITO USB 10-Channel 12-Bit AD Data Acquisition Module STM32 UART Communication USB to Serial Chip CH340 ADC Module	$49.65
A2.4	Adafruit ADS1115 16-Bit ADC (4 Channel with Programmable Gain Amplifier)	$45.40
A2.5	IC ADC 10BIT SAR 16DIP	$11.79
A2.6	Test Lead BNC to Wire Leads 4"	$31.26
A2.7	IC ADC 12BIT SAR 16TSSOP	$23.75
A2.8	USB Data Acquisition order	$109.64
TOTAL		**$316.67**

Halfway throughout the school year, it was found out that all the necessary equipment was not in possession as initially promised by the physics department. With the project now at risk of not being able to be completed, a solution had to be made on how to get the remaining amount of money to fund the rest of the project. Using Table 9.1, referencing the design and a lot of pondering, a list of remaining components was constructed along with its price and tabulated in Table 9.4 below. At the end it can be seen that a total of $6509.61 would be needed for the rest of the equipment. To achieve the rest of the money, a few sponsors were achieved. MarShield will be sponsoring all the radiation shielding for free. That has a value of around $15000 as they will be giving solid bricks of lead as can be seen in Section 3, the As-Built Design. Kert J. Lesker will give a discount on their vacuum products. CCR Products will be providing a product donation of a micro ion gauge (pressure gauge) and its controller valued at $2000. Supplying the remaining amount of $6509.61 was going to be promised by a combination of the Faculty of Science, Lassonde School of Engineering. In total from all sponsors (not including the Physics Department's original donation of equipment) the promised value of the fundraise came to be over $20,000.

Table 9.4: Summary table of all required equipment and it's associated price

Supplier	Part	Price ($CAD)	QTY	Total (not incl shipping)
https://www.lesker.com/flanges/flanges-cf-reducer/part/rf450x337t	REDUCING FLANGE,Z-L,4-1/2" OD TPD X 3-3/8"OD TPD FLANGE	164.23	1	164.23
https://www.lesker.com/flanges/flanges-cf-304ss/part/f0337x000n	FLANGE,UHV,SS,BLANK,FXD,3.375" OD	55.69	4	222.76
https://www.lesker.com/newweb/flanges/bellows_cf_hydraulicallyformed.cfm?pgid=unbraided	FLEX HOSE,SS,12"OAL,4-1/2"UHV FLGS,2-1/2"ID,.006" WALL	609	1	609
https://www.lesker.com/newweb/flanges/flanges_cf_304ss.cfm?pgid=1d33in	GASKET CLIPS FOR CF FLGS,10/PK	141.75	1	141.75
https://www.lesker.com/flanges/fittings-cf-nipples/part/fn-0337	NIPPLE,FULL,SS,6.43"OAL,3-3/8" OD UHV,2"OD TUBE	210.33	1	210.33

https://www.lesker.com/flanges/fittings-cf-crosses/part/c5-0600	CROSS, 5-WAY, SS, 4.00"TUBE OD 6"CF, A DIM = 5.31"	1,747.51	1	1,747.51
https://www.lesker.com/flanges/fittings-cf-crosses/part/c5-0275	CROSS, 5-WAY, SS, 1.50"TUBE OD 2.75" FLANGE, UHV FITTING, A DIM = 2.46"	375.99	1	375.99
https://www.lesker.com/flanges/flanges-cf-reducer/part/rf600x450	FLANGE,SS,UHV,REDUCING,ZERO-LENGTH,6"OD X 4 1/2"	223.9	1	223.9
https://www.lesker.com/flanges/fittings-cf-elbows/part/l-0600ml	ELBOW,SS,MITERED,4"OD TUBE,6" UHV FLGS,5.31" A DIM.	675	2	1350
https://www.lesker.com/flanges/flanges-cf-304ss/part/f0600x000n	FLANGE,UHV,SS,BLANK,FXD,6"OD	112.66	1	112.66
https://www.lesker.com/flanges/flanges-cf-304ss/part/f0275x000n	FLANGE,UHV,SS,BLANK,FXD,2.75" OD	21.06	2	42.12
https://www.lesker.com/newweb/valves/gatevalves_3position_ss.cfm?pgid=cf	GASKET, COPPER, 2-3/4" FLANGE, 1.895"OD,1.451"ID, 10/PKG	36.92	1	36.92
https://www.lesker.com/newweb/valves/gatevalves_3position_ss.cfm?pgid=cf	GASKET, COPPER, 6" FLANGE, 4.743"OD,4.006"ID 10/PKG	74.66	1	74.66

https://www.lesker.com/newweb/valves/gatevalves_3position_ss.cfm?pgid=cf	GASKET, COPPER, 4-1/2" FLANGE 3.243"OD,2.506"ID, 10/PKG	50.22	1	50.22
https://www.mcmaster.com/8546k24	Chemical-Resistant Slippery PTFE Rod 4" OD 1ft	224.28	1	224.28
https://www.mcmaster.com/5175k132-5175K38	Medium-Pressure, 3 Tube Size, 3-1/8" OD 5ft	123.28	1	123.28
https://www.lesker.com/	Bolts - various sizes	400	1	400
	Misc expense	400	1	400
Total incl tax				**6,509.61**

In total, with the value of the current equipment of over $21,400 (Table 9.2), $15,000 of lead, $2,000 of pressure measuring equipment and $6509.61 of the remaining equipment value, the total value of the antimatter containment unit will be $ 44,909.61. It should be iterated again that this value is without tax.

10 Preliminary Business Case

The antimatter containment project was designed to satisfy multiple stakeholder needs. The primary need for this project stems from the York University faculty of Physics stakeholder, and our project supervisor, Professor Matthew George. The secondary need for this project stems from the needs of various industry stakeholders that would benefit from the potential use cases of positron containment. The next two sections identify more of the specifics on how this project meets the needs of these stakeholders, but in the project's current status, and in future iterations of the project.

10.1 Physics Lab Development

To assess the antimatter containment unit as a viable experiment to teach 4th year physics students about antimatter, a SWOT analysis has been performed to identify the various strengths, weaknesses, opportunities and threats that are associated with this topic. The need for a physics lab is slightly different than an industry need, so the SWOT analysis shall be performed differently. The strengths and weaknesses will be categorized based on the effectiveness, or lack thereof, in conveying the physical concepts to the students who will be taking the class. The opportunities and threats will analyze the importance of the field of antimatter, and the need for it’s study versus other novel areas of physics study that could benefit from their own lab. The following SWOT matrix summarizes the key points which shall be discussed further in the following paragraphs.

Strengths	Weaknesses
- This project has access to high quality equipment that was used at CERN - one of the worlds largest and most well respected scientific institutions that leads in particle physics. It is unlikely that other labs would be able to receive equipment as high in quality. - The laboratory design is completely modular, allowing for pieces of the system to be upgraded as technology advances. This ultimately increases the longevity of the experiment and lab. - This physics laboratory will be the first opportunity for physics students to study antimatter via a hands on experiment at an undergraduate level in Canada. Such an opportunity will be a desirable feature for York University to promote to encourage potential incoming physics students to prioritize the university.	- The laboratory deals with very expensive equipment, and some aspects may require operation by lab technicians or TAs, thus students may not be able to interact with the entire system. - The radiation shielding is only sufficient for a fairly small radioactive source. Thus results from the experiment are very limited compared to other similar experiments done around the world.
Opportunities	**Threats**
- The field of antimatter research is a very hot topic in the world of physics, and being able to offer a lab that allows students to get hands-on experience with the topic allows York University to tap into this growing market. - The strength of being the first university to offer an antimatter lab at the undergraduate level gives York University the first mover advantage in this new field.	- Other fields of physics, such as quantum mechanics or the study of dark matter, are also gaining a lot of popularity in recent decades, and research in them may be another hot market that takes interest away from antimatter research. - The radiation shielding limitation that was mentioned in the weaknesses limits the extent to which research can be performed on the topic of antimatter, and the system restricts research to only one specific type of antimatter, the positron.

From a university perspective, the strengths and opportunities are clear. Being able to be the first in establishing an undergraduate physics laboratory that specializes in working with antimatter is valuable. Although there are other fields that may be equally as lucrative as the physics of antimatter, there is no definitive answer on which field is better, as they are all very novel. Even if students are unable to get a complete experience due to safety restrictions, even being able to get any hands on experience is leagues above other undergraduate students at other universities. From this, it is clear that an undergraduate antimatter laboratory is a good opportunity to capitalize on for the university.

10.2 Industry Use Cases

Aside from benefits to the university itself, many industries gain both the potential uses that this technology provides, and from students being able to have hands-on experience with a project like this. In the following SWOT analysis, strengths and weaknesses are categorized based on what students graduating from such a program will or will not bring to the industry as they move from academics to career. The opportunities and threats will analyze the potential use cases of this technology, and what other fields of physics may be able to provide that experience with the antimatter containment unit project does not.

Strengths	Weaknesses
- Students will be exposed to a variety of different systems including vacuum systems, high voltage electronics, radiation shielding, and magnetic/electric field generating devices. - Future employees with a bachelor degree will have experience that is only found elsewhere by people who have extensive experience in the field, or hold graduate degrees.	- Students may not have certain skills that could be learned by working on other final year projects, such as optics, which is a common focus of final year physics projects.
Opportunities	**Threats**
- New research suggests that positrons can be used to determine impurities in crystal structures by annihilating at areas of dislocations. These annihilations can be detected in a similar manner as is done in this project, allowing students working with this technology to aid in R&D facilities for materials labs.	- Students studying other fields such as quantum physics may be introduced to topics that can assist in computer science industries in the future, as the world progresses towards quantum computing.

Even from an industry perspective, it is easy to see the value that offering an antimatter laboratory at an undergraduate level would have. From broadening the skill set of those entering the industry, to offering unique knowledge that the industry may not be cognizant of, it is clear that there are many strengths and opportunities. It is a possibility that other fields of physics research may have many benefits for the industry as well, and the project team doesn't deny that. However, at the same time, it is unlikely that a laboratory dedicated to hands-on quantum research will be constructed, due to the highly theoretical state of the science.

11 Deviations From Plan

11.1 Design Change

11.1.1 Table Design Deviation

As mentioned in Section 3, a stress analysis was done on the table the containment unit will be placed upon. This is to make sure the weight of the lead bricks and the unit don't break the table and collapse the entire structure. The highest stress areas were found in contact zones between the shield and the table. It can be observed that the stress, strain, and displacement on the table is closer to the yield strength. This will ultimately result in failure for the table. A stronger table or a different option to support the system must be explored to rest the containment unit and radiation shields on it. From the stress analysis, it can be determined how strong the table will need to be in order to support the system. The Finite Element Analysis method has provided a good evaluation in the design phase and has shown the values of stress, strain, and displacement as it **did not satisfy the safety standards**. The weight can't be controlled much since the design is very fixed at this point in time but the supports can be modified to reduce the propagation rate of existing fatigue and buckling in the support. Another way to minimize mass would be to minimize the mass of the shield design. However, that might affect the shield effectiveness and lower the effectiveness to prevent the gamma rays penetration. This is not a very viable option as it may affect safety regulations.

11.1.2 Lack of Equipment

At the beginning of the second semester we found out that the Physics department did not have all of the equipment required to build out our design coming out of CDR. We also found out that the equipment they have did have did not reflect what we have in our design. Due to this we had to completely redo the design of the vacuum system up until the end of the TR as we were trying to work with the equipment given to us as best as we possibly could. Due to the redesign of the vacuum system assembly, work on the radiation shielding came to a halt as the vacuum assembly design had to be finalized first before we could design a custom shield around it. The changes in the vacuum system were reflected in the electrode design, the size of the piping within the vacuum system, the orifice implementation within the electrode setup and other vacuum parts that were needed to complete the vacuum assembly setup. We had to keep cost in mind while doing the redesign as mentioned in section 11.2.

11.2 Funding

In the beginning, it was originally thought that all necessary equipment was possessed by the physics department. Excluding some minor electrical equipment such as SD cards, the major thing required to be bought was lead shielding. Since we were short on equipment, as mentioned in section 11.1.2, we had to find a solution and fulfil the project procurement needs before the end of the semester which was in 3 and a half months. In doing so we began reaching out to industry sponsors where our project would prove to have a strong business sense. We utilised our 'USP' which was the fact that we were one of the first undergraduate student team that was working on an antimatter trapping project. Normally a project like this is done at institutions like CERN and very rarely at a university level, especially at an undergraduate level. By projecting the potential impact of the success of this project and marketing the corresponding PR that the potential sponsors could get, we were able to secure 6 sponsors. These included, Lassonde School of Engineering, York Capstone Network, Faculty of Science and the Physics department, CCR Process Products, Kurt.J. Lesker and MarShield. MarShield will be donating radiation shielding valued at $15000 as they will be giving solid bricks of lead as seen in Section 3, the As-Built Design. Kurt J. Lesker will give a discount on their vacuum products. CCR Process Products, will be providing a product donation of pressure measurement equipment valued at $2000. York Capstone Network, Faculty of Science, the Physics department and Lassonde School of Engineering will be sponsoring the remaining expenditure of the project amounting to $6509.61 (see section 9). A total amount of over $20,000 was going to be raised from these 6 sponsors.

The sponsorships were categorized as internal and external sponsors. See the Appendix in Section 15.3 for copies of the 2 proposals that were sent out to the respective internal/external sponsors.

12 Failure Report

Many of the requirements that were taken upon have been completed. The requirements that haven't been completed are the ones requiring the full assembly of the system which couldn't be done at the time due to lack of funding. As previously stated in the Test Review, one of the main issues was with the small scale vacuum setup. The small scale vacuum setup was not reading the desired pressure value. After many iterations and tests, the problem was discovered to be a faulty gauge. This was a fulfilling stepping stone to accomplish as this meant the vacuum setup could now be implemented and tested on a full scale model once funding was secured and all the necessary parts came in.

The development of the PMT which is the detection system off the positrons, combines the signal and setup tests outlined in the TRR. It was realized that the operation status of the photomultiplier tube can be combined with the signal test, and as long as the signal test is successful, then the setup test is verified too. If the signal test had failed, we could have performed the setup test; however, since the signal test worked, we were able to save some time.

After connecting the power supply to the photomultiplier tube, and the photomultiplier tube output to the oscilloscope, the radioactive source was brought near the input of the photomultiplier tube. As the radioactive source was brought closer, the average voltage on the oscilloscope increased, and as the radioactive source was taken away, the average voltage decreased as expected (voltage decrease was proportional to square of difference). This confirms that the photomultiplier tube was set up correctly, and the hardware works as expected.

The part that created the most issue was the fact that the signal reading in from the photomultiplier tube into the Raspberry Pi via the analog to digital converter, was not sufficient. The maximum sampling rate of the device needed to be much greater. In fact, even after iterating a few times on the design and trying different analog to digital converters, failures kept occurring. So, in order to resolve this, we replaced the analog to digital converter to a version that can handle a higher system clock, thus a higher sampling rate. Now, after reoptimizing python code the obtaining values from the PMT was more readable and detailed

Overall, the requirements that were started were able to be completed or mostly complete. The remaining requirements are the ones that haven't been started and tested yet due to funding and the completion of the full scale model. As stated in Section 4.5, no more tests were able to be completed due to the global pandemic so no non-conformances are remaining nor have any new non-conformances risen since the TR. All previous non-conformances have been resolved and can be seen in the TR linked below.
TR:
https://docs.google.com/document/d/1pJD6qYrO9TFsymHqptrFiJxnL6SMuQgnRIKNUhTrzvk/edit?usp=sharing

13 Lessons Learned

13.1 Team Reflection and Caveats

Undertaking this project was a monumental task, and while the team had many successes, there were a lot of areas where work could have been performed better. Having worked on various engineering projects before, the team was eager to start working immediately. However, unlike other engineering projects that the team has engaged in during their undergraduate degrees, the scope of this project was much larger. Due to this large scope, the project needed to be meticulously planned to ensure that things got implemented in the right order, and redundant tasks were not performed. Although the team tried best to plan the project, it is unfortunate that sometimes things got overlooked.

As mentioned previously, the team encountered a major pitfall when an issue occurred during the procurement process when the team thought certain parts were available that in fact were not. This issue drastically changed timelines as well brought up budgeting concerns. This could have easily been avoided if the project was better managed at the beginning. The first task that should have been undertaken is the stockpiling of available parts and materials. If this had been done, the team could have created a design around the available parts, and have more time to order parts that were crucial, but unavailable.

Outside of issues within the project, there were sometimes also issues within the team itself. There were times where the stress of the project created an environment where team members would act hostile towards each other. This was especially sad to see as many of the team members entered this project as close friends. One way our team aimed to solve these conflicts was to bring in a mediating party (who was also part of the team, but not directly involved in the conflict) to listen to each party, and decide the best path towards conflict resolution. However, since this member was also part of the team, this was extremely hard to do without bias. Despite these potential biases, it seems the mediator was able to settle the conflicts in a manner that allowed the project team to work together again harmoniously. In future projects, this could be handled better by choosing a party who is not part of the team to act as a mediating body before the project begins. This way, it can be ensured that the mediator brings in minimal bias.

At the end of the day, the team was able to bring the project to a stable state, despite the various challenges. As it stands, the project is in a state that can be easily continued as soon as work can be done again, and much of the team is very eager to see this project through to completion. This highlights how much the team has grown throughout the project, that even though there were times where relations between team members was rough, the team would still like to come together to finish what has been started. Even though the project goal could not be met at this time, the team believes that there has been much success. Overall, we are excited to see where this project will go in the future.

13.2 Individual Reflections

Yaseen Al-Taie

As a student in space engineering, I have learned to grasp the connection between math and physics, and how they can be applied in our daily lives. All the knowledge, skills and experience that I have accumulated over the span of my undergraduate degree has been poured into this project. Moreover, the last 5 years at Lassonde taught me how to work with people from all different walks of life, and how to be flexible depending on the circumstances present.

As part of the ENG 4000 engineering graduation project(capstone), we formed a group of people with different expertise ranging from software and electrical to mechanical and physics. Since our project deals with high energy positrons and radioactive radiation, therefore, we need to approach our experiment with caution to avoid possible injury. We do this by following all the standards set by York University on how to deal with radioactive sources. My studies cover objects above our atmosphere, and how these objects are exposed to dangerous radioactive emissions. I used this knowledge in our project, to understand how to protect my colleagues during their time experimenting. My mission in this project is to build protective lead shields around the apparatus used for experimentation. To complete this task, I had to share my knowledge in radioactive material with my peers, in the physics department. We had to cooperate to figure out the optimum material, thickness, shape and distance from the source in order to eliminate radioactive emissions from harming our colleagues.

Being part of this project, especially with my tasks, has burdened me with the responsibility of the safety of my colleagues during their work. Achieving a safe environment for the project could not have been possible without the aid of my peers in the physics department and the support of the engineering team. My other mission during this project was to find a harmony between the school of physics and the school of engineering, since physicists and engineers overcome problems in a different manner which has caused a miss-communication. However, our ability to communicate and learn to work as a team has proved to be very valuable in completing our tasks efficiently and safely. Even if a member of our team has been difficult to deal with, we always remind each other that we have goals to achieve before deadlines and are powered through them.

From the beginning, we aimed to perform our project in a safe scientific manner and showing engineering proficiency because this would be one of the first times Canadian undergraduate students attempted an Antimatter Containment Unit project. As we know from trapping and detecting positrons, we can achieve results that help us produce instruments that treat cancer and help enhance our understanding of space physics.

Even though I had the task of setting up a shield, I was always involved in the bigger picture of all aspects over the project. From a personal standpoint, I have been through multiple experiences during this project with third party businesses, conversing with physics professors, a higher understanding of anti-radioactive materials for shields used in absorbing the source's emissions, creating a healthy work environment always aiding your colleagues and asking for help when needed.

Mohammad Khan

I'm very glad that I chose the antimatter containment unit as my capstone project. Being a mechanical engineer you get to learn lots of different subjects as it is a very broad area. Although, being a mechanical engineer, particle physics isn't taught to us and I wanted to take the initiative to broaden my knowledge on something I didn't know and originally thought didn't have any real world applications. I've learned quite a bit from the theoretical, technical and other perspectives.

Learning about antimatter and the physics involved with them was a steeper climb for me than I initially perceived. There was a lot to learn about such as how detailed the vacuum system design can be, how difficult modelling and calculating molecular flow can be. As a mechanical engineer, we only deal with mass flow that has viscous and inertial forces. This was brand new territory for me and the rest of us. We started this project way back before the semester even started and got the necessary radiation training at York University. One thing I would have done differently is that I should've read up on it even more and gotten a larger "head start" than I initially thought I had. I should've tried to attain a better understanding of the underlying physics waiting ahead so I could make my time more efficient for the design and report aspects of the project.

Due to the complex nature of antimatter, explaining the subject during presentations and in reports was a challenge of itself. The requirements of many of the reports were to make it so that a competent non-expert in the field could design and test the containment unit. This was a challenge for me and the others because simplifying an already complex subject is difficult to do. This was a good problem to try and deal with because in a real world scenario, your coworkers may not be engineers, so technical and theoretical knowledge will have to be simplified so that they can understand what's going on and why certain decisions were made. Some things we did to try and simplify it were to leave out anything too technical and leave out all the numbers. One thing we could've done to try and simplify was to have an individual not in our line of work to go over what we've done and see if there was something that was hard to understand or needed simplification.

The scope of the project was a lot more broader than I initially thought. Calculations had to be done for the radiation shield, vacuum system, nitrogen injection system, magnetic modelling and the programming components had to be made. With all this under our belt, the additional problem of finding out that we did not have all the components needed was another problem that had to be resolved. We could've tried to determine what components were not available from the beginning so that the design could've been adjusted towards a different alternative.

One thing that I tried to do is to enjoy the project overall, it is a fun and interesting topic to do a project on but oftentimes, you're in a position where you just want to get certain things done and out of the way like reports and presentations. Sometimes I'd forget to just enjoy the journey and the project itself. I am definitely proud of what me and my team members were able to accomplish this year and will continue to do so when I look back on it.

Due to the COVID-19 pandemic, this project was unable to be fully completed. Me and my team members have accomplished quite a bit during this past year and would like to continue the project from where we left off when we can. We are not ready to give up and will try to continue the project in the future.

Ashifa Hassam

I am happy to have been part of the Antimatter Containment Unit project for ENG 4000. Through the different stages of this project, I feel as though I gained knowledge and practical experience that I will be able to use in my future endeavours. Being part of this project encouraged me to apply what I have learned throughout my mechanical engineering degree while also expanding my knowledge in physics. Parts of this project were initially beyond my scope of knowledge however, throughout the process, I gained confidence in my abilities to think outside the box and use analytical skills when needed.

Our team consisted of students from the mechanical, electrical and space engineering departments as well as students from the physics department. It was interesting to see the different ways that we all approached problems, based on our backgrounds. While this sometimes led to miscommunications, it was often an advantage to have multiple perspectives. I really enjoyed working with my team and getting to know the students from the physics department. I believe we all had the opportunity to show our strengths while being open to learning from others.

From the beginning, the most important concern was that of safety. This project entailed being exposed to radiation, so it was imperative that we had the adequate knowledge and understanding of procedures to be followed. By attending the radiation safety training in the summer, before the start of the school year, we were able to familiarize ourselves with these guidelines and I think it was a really good idea to be proactive and do this ahead of time.

As previously mentioned, at the beginning of the project, I did feel there were certain aspects beyond my scope of knowledge. It took time and effort to familiarize myself with concepts that I had known previously. Being able to have discussions with the physics students, as well as my fellow engineering teammates was beneficial for this. Additionally, as these conversations progressed and as I completed my own research on specific topics, I gained confidence and found methods that were more effective and efficient for me. As such, I was constantly learning throughout the duration of this project.

This project also gave us a chance to apply the communication skills we have been taught and work together to achieve a common goal. There were times when group members did not see eye to eye, but overall, I believe we were able to solve the disagreements in an effective manner and allow for everyone to be heard.

Speaking to the actual content of this project, I wish we could have had the chance to try and finish it physically. Due to the pandemic, we were unable to continue building the unit which was a disappointment for all of us. I think this project has great potential and I know that it is a collective hope that we will be able to come back, on our own time, to try and proceed with it. We were very fortunate to have been able to use equipment donated to us from the physics department, from a similar project that had been done a few years back. The project would have been much too expensive to proceed with had we not had this equipment. This project was also meant to be used as a lab for a physics course, which I think would be of interest to many students. On a larger scale, the study of antimatter has many applications, especially in medical science.

I was able to work on many different parts of this project, not just the ones that were more related to mechanical engineering. This was enjoyable for me as I was able to expand my knowledge and find different interests that I may have otherwise not discovered. I thoroughly enjoyed working with my teammates and hope that if this project is not completed by us, another group will be interested in pursuing this for their capstone project.

Hunter Schofield

Working on this project has been one of the best experiences I have had in my academic career. Studying engineering is hard, and although there is no doubt that what I learn in my classes are so useful to so many industries, it seldom feels that way. However, working on a project like this is different. Being the culmination of the engineering degree, this project has allowed me to take what I have learned, and apply it in a way that is tangible.

Aside from being a project that allowed me to see all that I have learned be applied, it was also a project that allowed me to expand my knowledge. As a space engineering student, I have some knowledge of electronics, software, vacuum systems, and radiation shielding; however, what was required for this project was much more. On this team I worked mostly on the electrical and software systems, and most of my learning took place through failure. Specifically, my on-going task was to design and implement the detection module. The initial design I created was correct in theory; however, lack of attention to detail created an issue. The part I had originally chosen to read the signals from the photomultiplier tube into the Raspberry Pi, the analog to digital converter, was not sufficient. The maximum sampling rate of the device needed to be much greater. In fact, even after iterating a few times on the design and trying different analog to digital converters, failures kept occuring. It wasn't until trying the 4th ADC that a usable result was achieved, but the results were still poor. Although these failures kept occuring, in the end, I was able to design a system that worked well. Now, I understand the world of analog to digital converters much better, and feel confident in how I should choose them, should I need them for future projects.

This process of repeated failure was humbling to say the least. Although electrical engineering is not my background, I have worked with many different electronics devices in the past as a hobbyist, and considered myself fairly knowledgeable in the area. Going through this process taught me that it doesn't hurt to go over my designs a few times, and consider potential failure modes. In fact, this is something that can apply to many different areas of design, not just in the design of electrical systems. This is yet another example of how working on this project has made me a better engineer, however, this time instead of expanding my technical knowledge, I have learned more about good engineering processes.

I am certain that working on this project has changed me for the better. I am confident now that I have the resources to excel in my career as an engineer. Much of this is thanks to being able to work on a project with such a large scope and impact as this. Not only am I able to say that I worked on a project pertaining to cutting edge physics research, but I held a managerial role as well. On top of this, through the team's hard work, we have the possibility of setting a milestone for physics in Canada, by being able to provide the first undergraduate lab pertaining to antimatter for the country. I am truly proud of the team's hard work and dedication, and I am excited to see how this project will develop in the future.

This brings me to my final note. It is no secret that unforeseen circumstances had to put a pause on this project, as it has with many others. However, after all the time I have poured into this project over the last 10 months (a lot of work was done setting up the project before September), I am not ready to give up. I am excited to pick up this project again as soon as the global situation permits, and I would like to see it through to completion. I am certain that in the near future we will be able to see the first antimatter containment lab at York University!

Kareem Samuels

The antimatter Containment unit project was that entity I needed to integrate all the tools attained in my arsenal throughout my 5-year journey of being an electrical engineering student. The experience that this project brought to me was the best conclusion to my undergraduate degree. The project really encompassed all the lessons and theory taught within my program, from power electronics to signal analysis. Yet, it was able to incorporate the experiences of engineering design within the first year and understand the challenges of Project management, such as time management, presentations etc. within the 2nd year. However, the most impactful factor about this project was the way it was able to include the best of both worlds, Engineering and Physics. To see how both faculties mesh in a project really took the depth of what I was taught to another level of thinking. This truly allowed me to harmonize all the accumulated knowledge of engineering and physics. Thus, being able to engineer physics firsthand.

Although this was a project to integrate my electrical engineering knowledge by applying what I learned as well as sharing my technical knowledge with my team members, it also allowed me to branch out of my comfort zone and vastly expand my knowledge. As an electrical engineering student, I have a strong foundation in power electronics, and signal analysis. Not only did this project allow me to dig deeper and sharpen my software skills and physics but introduced me to vacuum systems and antimatter. On this team, I worked mainly on the vacuum system and had to teach myself extensively to understand the sensitivity of the vacuum system as well as the importance of maintaining extremely low-pressure levels to optimize success in the detection of positrons. As well as the Emergency vacuum stop circuit, a safety measure ensuring that the vacuum system can turn off without harm to itself and other equipment. This project was truly a humbling experience as it taught me to rapidly learn from my failures to achieve deadlines. In theory, the vacuum system would work in an ideal environment, but I had to tweak and take into the account of the tolerance of the system that I am using and design limitations. I followed suit with the vacuum system design that I created based on the idea that the given equipment was calibrated to the appropriate measures. However, after building the system and conducting numerous tests I have realized that I needed to be a lot more attentive to detail. This also taught me to do the minor steps on ensuring each individual part will accomplish its desired task. For example, when building the system, the pressure readings were wrong which led me to think that there was a leak in the unit. After decomposing the parts I learned that there was a faulty pressure gauge preventing me from conducting the tests for the emergency stop circuit. Now I understand the importance of individual testing and the sensitivity of vacuum systems.

Due to not paying attention to detail and not considering the intermediate steps has taught me a major lesson and is a huge reminder of the engineering design process and the best approach to ensure success in your designs. A big takeaway from this experience is that it is fine to make mistakes but have a plan of potential issues that may occur with the design and possible resolutions. Doing so will make the testing phase more efficient. This is a practical lesson that I can apply in my daily life but especially in my engineering career. Again, this reiterates the fact that this project not only broadened my technical abilities but helped me perform better engineering practices to help me build the confidence in being a better engineer.

The experiences of this project helped me to build confidence in myself as an engineer. Also, it reassured myself that I do have the ability to apply what I know within an environment that I had to get comfortable with. In addition, I learned that I do have a strong ability to learn new content quickly, especially with the guidance of my team members that are willing to share their expertise in the areas that I lack. It was truly an honor to learn from my peers but to be a part of a project that has great potential to set a milestone in Canada for physics. Now, due to unforeseeable circumstances of the COVID-19 pandemic, our group members' extensive hard work had to come to a halt. Especially at a time where we gained a lot of success in our sub system testing and sponsorships were flooding in. I hope that things are able to resume as normal as I would love to finish what we started and see a successful outcome in our efforts.

Akshay Sood

The beginnings of this project are deeply rooted within my journey through university. Having wanted to go into Physics and Astronomy for the majority of my life; I was one day given no choice but to leave that dream behind and pursue Mechanical Engineering. Now coming into engineering, I had absolutely no idea of what it entailed and what the path to becoming a Mechanical Engineer actually looked like. As I was attempting to process this sudden change, I came across an article about a group of mechanical engineering students from Concordia University that built a “Particle Accelerator” for their Capstone Project. Having always had a passion for physics and astronomy, this headline intrigued me and so I continued to delve into their project and the significance of what they achieved. I was very inspired by what that team had done and decided that I will do something like that for my Capstone Project, something exciting and unheard of, something that combines my passion with my academic vocation.

Over the next several years I continued through engineering with this vision in mind. I had been in contact with Professor Matthew George over the last 2 years for a potential project available from the Physics Department at York University. But it was not until the beginning of Summer 2019 that I came across this project, as it was proposed by Prof. George. At this point, the team was given a few readings to do as they pertained to establishing the knowledge foundation required for the project. Looking back, I should have done more research during the summertime than I did, as even with everything, the knowledge gap to cover was very significant. I also should have been more adamant in communicating the importance of conducting and following through with the research to my fellow teammates. This would have at least attempted to solve the significant knowledge gap that was present within some team members.

Taking on the role of Project Manager within this project was both an extremely rewarding and strenuous experience. This, I believe, is somewhat reflective of real life and so the learnings that I have been able to take away have been immeasurable. As the project manager, I had one goal in mind, which was the success of this project. Having a diverse group of people not only from an academic discipline perspective but also from a communication standpoint was both an asset and at times a challenge that had to be overcome. Simple things like scheduling meetings were challenging due to vastly different schedules and hence availability. However, it was the understanding of how communication can be individualistically streamlined so that we can operate at a higher efficiency, that took the most amount of effort. And even after all of this, we did not reach peak operating efficiency as a team that we had wanted. However, my learning here lies in the early identification and understanding of how individuals work from the get-go. There are multiple dynamics within a team that one has to consider in order to make sure that the ball is rolling as smooth as possible. The earlier they are understood, the quicker problems and challenges can be overcome both as a team and individually. Having this skill in the workplace means that you can be more proactive and reliable for your team, even if you are not leading them. A leader shows how it is done and implants a vision of the end goal within the team so that all members are equally motivated and know exactly what is at stake. Within this project, even though the vision was well communicated, there were times where group members did not seem as motivated and due to that work output as a whole was slow to non-existent. It was during these times that I had to really step up and make sure that we continue, no matter how bleak the next day looked. Within life, I believe that the skill of positively handling adversity is very important. My time within this project helped me refine that ability to do so. With exposure to this at this stage of my career, you cannot guarantee that the reaction will be positive every time, but rather you understand how you work in such situations and learn to adapt for the better.

The course of the project shifted over the last 8 months as we went from having all the required equipment to build the experiment out to finding out that we actually do not. Well not to the extent that we thought previously. This one event changed the course of the entire project. In order to move the project forward, we had to find a way to fulfil project procurement needs as quickly as possible. This led me down a dual path; one that was surrounding the fundraising of funds and the other the being the continuation of the project work ad hoc. At this point, my entire focus was on the project as I prepared proposals to send to potential sponsors; both within York University and externally. Due to this sudden need to raise money, our design ended up changing several times over in order to minimise cost. Going through this, at times I was spreading myself out too thin, as promised work was not being delivered upon. Taking on any additional work meant that I now had to continually re-formulate my strategy of completing the tasks on hand. As I did this, I learnt how to identify and overcome work bottlenecks as they came up. By going through the process of assigning tasks to team members and analysing the end results, I gained a better understanding of how to set up the team for success and assign tasks accordingly.

14 Self Evaluation

Criterion	Self-Evaluation Ranking	Justification

Explain the importance of compliance with the Professional Engineers Acts and other relevant laws, regulations, intellectual property guidelines and contractual obligations and follow best practices	Exceeding Criterion	We followed all health and safety guidelines throughout the project. Radiation safety training was taken back in August of 2019. The YorkU Radiation safety group would have eventually come in and tested the room for radiation levels over the standard.
Employ strategies for reflection, assessment and self-assessment of team goals and activities in multidisciplinary settings	Exceeding Criterion	As can be seen in Section 14, Lessons Learned, all team members have reflected on their experience in the project and what they've accomplished and learned. A group reflection has also been done to show the lessons we've learned as a team and what we've accomplished overall.
Adhere to written instructions in a professional context	Exceeding Criterion	Content is all professionally written with first person only being used in the Lessons Learned and Deviations From Plan. The rest of the report is written in 3rd person.
Evaluate critical information in reports and design documents	Exceeding Criterion	Critical information can be seen in Section 3, As-Built Design.
Appraise possible improvements in the problem solving process	Exceeding Criterion	The next steps in the project have been discussed many times throughout the report. A new table will be needed to hold the system.
Justify the strength and limitations of the solution and make recommendation for possible improvements	Exceeding Criterion	As previously discussed, the limitations of parts of the design were stated. The table couldn't support the weight of the system.

15 Appendix

15.1 Appendix A - Requirements

15.1.1 Met Requirements

Requirement: P-FUN-10 Instrument Design **Requirement Type:** Functional	**Requirement Source:** Project Supervisor
Description & Justification: The instrument design shall be able to fit on at least 2 lab tables that are 60 inches in width and 120 inches in length when combined. Since the end goal of this project is to set up a lab for 4th year physics students, the project needs to be able to fit on the tables provided in the physics lab.	
Nature of Validation: Our team has met with physics professors and inspected physics labs with similar projects to understand what dimensions are required to house an assembly as large as the one in our design. Upon doing this, we were able to validate this requirement as necessary, since it would be very difficult to complete the project without a table.	
Nature of Verification: Our team performed an early analysis by modelling the table in solidworks before creating a solidworks assembly to ensure that the containment unit assembly can fit within the dimensions of the table. After the radiation shielding was ordered, our team also performed stress analyses on the tables to ensure that they can support the weight of the system.	

Requirement: P-FUN-20 Detection System Assembly **Requirement Type:** Functional	**Requirement Source:** Project Team
Description & Justification: The containment unit shall incorporate a detection system capable of detecting the annihilation of the positrons above the level of background noise, as measured prior by an oscilloscope.	
Nature of Validation: The goal of the project is to set up a physics lab for 4th year physics students. To ensure they can get maximum benefit from the lab, there needs to be a detection system so that the data can be visualized. Upon completion of the system, we ensured that the data provided by the detection system was sufficient for the data visualization required by the physics lab. This was done by working with 4th year physics students who assisted in the development of this project.	
Nature of Verification: The functionality of the detection system was verified in multiple stages. The first stage used an oscilloscope that was connected to the photomultiplier tubes which can measure the gamma rays given off when a positron annihilates. By	

introducing the radioactive source to the end of the photomultiplier tube and seeing a large response on the oscilloscope, we were able to verify the detection system was assembled correctly. In the second stage, the oscilloscope was replaced by an analog to digital converter which was then fed into a Raspberry Pi. After writing some code to parse the incoming data, we were able to see the same response that occurred on the oscilloscope, thus verifying the full assembly of the detection system.

Requirement: P-FUN-40 Modular Design	**Requirement Source:** Project team, York Physics Faculty & Students
Requirement Type: Functional	
Description & Justification: The design of the unit shall be modular so that the project team can work on many parts of the project simultaneously. Due to heavy time constraints, there is a great need to increase the efficiency of the project where we can. One way to do this is incorporating a modular design so that various components can be fabricated in parallel before being assembled simultaneously. This will also allow the team to test various components in parallel before doing one integration test to ensure the system as a whole works as expected. The modular design also assists physics students performing the lab to tackle the problem more easily since the whole system is separated into different parts; electrical subsystem, radiation subsystem, etc.	
Nature of Validation: Our team held various group meetings throughout the year to assess the remaining time, and ensure that a modular design was the best approach for the system. As components of the system were designed, our team consulted the physics students who were assisting with the project to ensure that the components encompassed enough information to be considered one topic within a lab setting.	
Nature of Verification: Each component went through an exhaustive integration test to ensure that their assembly with adjoining components did not introduce a failure within either. There were various results from these integration tests which will be discussed further in the compliance analysis section of this report.	

Requirement: S-PER-10 Power Constraints & Minimization	**Requirement Source:** Project Supervisor
Requirement Type: Performance	
Description & Justification: The current draw of each module shall not exceed the 15 Amp limit provided by the various rails within the lab. Since this experiment is being set up as a physics lab, it needs to be able to run off the power rails provided by the labs in the Petrie building. Thus, the current draw cannot exceed 15 amps for each module, since any more would cause the system to fail.	
Nature of Validation: Throughout the design and assembly process, our team confirmed the maximum power draw of each module to ensure that it was within the margins	

expected. This way, the team could ensure that the requirement was valid as is, and did not need to be altered to allow for multiple modules stemming off the same rail, or for an external power rail to be required.
Nature of Verification: Our team visited various labs around the Petrie building to understand how many different power rails were available for us to use. Upon doing so, we were able to determine that there were enough unique rails to support our modular design, so as long as each module does not exceed a 15 amp current draw, then the various physics labs in the Petrie building will be able to support this experiment.

Requirement: P-INT-31 Geomagnetic Field Detection	**Requirement Source:** Project Supervisor, Project Team
Requirement Type: Interface	
Description & Justification: The Earth's geomagnetic field that intersects the experiment laboratory shall be measured to within the order of 0.001 milli Tesla in accuracy. Since much of this experiment requires the use of magnetic fields to maneuver the positrons, it is crucial that we are able to understand how the Earth's geomagnetic field might affect our experiment, and mitigate it accordingly.	
Nature of Validation: Throughout the design phase, our team considered different scenarios that the Earth's geomagnetic field would have on the positrons in the system. Even for hypothetical scenarios where the Earth's geomagnetic field is weaker than it would be, the quality of the experiment diminished, thus validating the need to measure the magnetic field to be able to mitigate it.	
Nature of Verification: To verify the results of the measurements, multiple measuring devices were used on various dates to ensure that fluctuations in measurements were minimized. The project team was able to determine a consistent reading across the devices and dates, thus verifying the measurements.	

Requirement: P-INT-32 Geomagnetic Field Mitigation	**Requirement Source:** Project Supervisor, Project Team
Requirement Type: Interface	
Description & Justification: The Earth's geomagnetic field within the containment unit shall be mitigated by a minimum of 90%. The Earth's geomagnetic field will have an effect on how the positrons travel within the system, so it is important to remove as much of the geomagnetic field as possible to ensure the results of the experiment are as expected.	
Nature of Validation: Similar to the above requirement, after considering the effects of the geomagnetic field in the design phase, it was determined that the field needed to be mitigated in order to improve the results of the experiment. This design phase analysis validates the requirement.	

Nature of Verification: To verify the results of the mitigation setup, the same equipment that was used to measure the geomagnetic field in the lab was used to test the magnetic field within the containment unit. It was noticed that the magnetic field was different by the same amount as the Earth's geomagnetic field in that area, thus verifying that the geomagnetic field had been mitigated.

Requirement: P-REG-10 Radiation Shield Modelling	**Requirement Source:** Project Supervisor, Project Team, York University Health and Safety Department
Requirement Type: Regulatory	

Description & Justification: A model of the radiation flux through the radiation shielding design shall be made in order to analyze the dose received past the shielding for various configurations and materials used. To be allowed to conduct the experiment on campus, the project team needs to ensure they comply with health and safety regulations made by the York University health and safety department. Thus, a radiation model and analysis needs to be created to ensure that the design can comply with regulations.

Nature of Validation: Throughout the design and conception phase, the project team met with York University's physics health and safety branch to confirm the regulations around radioactive materials for use in the project. This process validated the need for the model of the radiation shield as it gave us specific constraints to consider in order to be allowed to proceed with the experiment.

Nature of Verification: A preliminary design was created, and checked with mathematical models by hand. This revealed a good design that was capable of mitigating the radiation that would be emitted from the source. Upon completion of this, solidworks was used to create a full model of the radioactive shielding and further calculations were performed using software analysis tools. These calculations matched the ones expected from the hand calculation, verifying the model.

Requirement: P-PRO-10 Instrument Design	**Requirement Source:** Project Team
Requirement Type: Procedural	

Description & Justification: The laboratory workspace allocated to the project team shall be cleaned of all unneeded pre-existing materials, and all required materials shall be stockpiled in the room for later use. Before the assembly phase, most of the required materials were located in various storage areas. The stockpile needs to be created so that the project team can take inventory and ensure that all the parts required for the project are available.

Nature of Validation: Frequent meetings were held with the project supervisor to get an inventory check of various storage areas around the Petrie building where the project team could have access to materials. It was found that not all the materials required for

the project were available in these storage areas, requiring the project team to order the missing components. If this requirement was not set, it would have been much later in the project schedule that this would have been discovered, and the project would have likely failed very early. This scenario validates the need for the requirement.
Nature of Verification: A checklist was made with all the required materials and equipment for the project. As the stockpile was complete, an inventory check was conducted against the checklist, and the checklist proved most items were in the stockpile. The remaining items were ordered as required, thus verifying this requirement.

Requirement: P-PRO-20 Detection System Calibration	**Requirement Source:** Project Supervisor, Project Team
Requirement Type: Procedural	
Description & Justification: The positron detection system shall be calibrated before experiment operation to ensure that the data being output is valid. This is important because if the detection system is not calibrated, then the results cannot be used to infer the operational status of the system.	
Nature of Validation: After the assembly of the detection system was complete, various tests were performed to ensure that the detection system behaves as expected and would need to be calibrated every so often. After these tests were performed, it was determined that the detection system did not need to be recalibrated before every experiment, but instead needed to be recalibrated on a weekly basis, validating the need to calibrate the system periodically.	
Nature of Verification: An oscilloscope and a raspberry pi were used to gather data in the detection system. Basic calculations were also performed to estimate the output voltage based on certain distances of a test radioactive source being held from the photomultiplier tubes. Tests were performed to ensure the oscilloscope and raspberry pi readings were similar, and that both were in the order of magnitude expected by the basic calculations. When all three of these methods would agree, this requirement would be validated.	

Requirement: P-PRO-30 Detection System Verification	**Requirement Source:** Project Supervisor, Project Team
Requirement Type: Procedural	
Description & Justification: Upon the assembly of the detection system, various verification tests shall be performed on the detection system to ensure that it can measure the positrons emitted from the system. This is crucial because if the detection system is not able to detect positrons, then the results from the experiment will be unknown.	
Nature of Validation: The need for this requirement is a core component of this project. If	

the detection system is unable to detect positrons, then the results of the experiment are useless, and the main goal of the project cannot be achieved. Thus the need for this requirement stems from the goal of the project; to contain positrons.
Nature of Verification: A test radioactive source was used with a known emission rate and half life. By introducing this to the detection end of the detection system, and analyzing the output on an oscilloscope, it was possible to verify that the results being displayed matched the theoretical output of the radioactive source. Thus, positrons were being detected and this requirement was verified.

15.1.2 Partially Met Requirements

Requirement: P-PER-20 Amount of Positrons Detected	**Requirement Source:** Project Supervisor, Industry Stakeholders
Requirement Type: Performance	
Description & Justification: The minimum rate of positron detection capable by the detection system shall be at least 10,000 positrons detected per second. This is the minimum amount of positrons required to be useful. Any less positrons, and it is too difficult to study their interactions, and their release would not be in a sufficient quantity for use in engineering applications.	
Nature of Validation: During the design phase our team performed analyses by reading research papers given to us by our project supervisor. These papers outlined similar experiments and gave us an insight on the minimum quantity of positrons required for our setup as identified in this requirement.	
Nature of Verification: By analysing the signal on the oscilloscope that was observed, similar to the detection system assembly test, it was possible for the team to correlate a voltage level to a positron quantity. By doing this, we were able to determine how many positrons per second the radioactive source was emitting. However, this Requirement is listed as partially met since we were unable to perform this test on the entire system as a whole, and were not able to verify this requirement against the final assembly.	

Requirement: P-INT-10 Data Visualization Software	**Requirement Source:** Project Supervisor, York Physics Faculty & Students
Requirement Type: Interface	
Description & Justification: A user interface shall be developed for the purpose of data analytics and visualization. As this lab is being set up for 4th year physics students, it is crucial that the data from the experiment can be easily interpreted and downloaded if necessary.	
Nature of Validation: Throughout the development phase of the software, our team interfaced with the physics students that assisted with the project to understand the needs of students who would be in their place in the future labs. By doing this, we were able to	

validate the software as it was being developed to ensure that useful data was being displayed to the user.
Nature of Verification: As different modules of the software were developed, various tests were performed alongside our helping physics team to ensure that the data received from the Raspberry Pi made sense and would be of relevance for the future physics students. Unfortunately, while a large portion of the software was able to be complete, the full UI was not able to be realized, which is why this requirement could not be fully verified.

Requirement: P-INT-40 Turbomolecular Pump Stopping Mechanism	**Requirement Source:** Project Team
Requirement Type: Interface	
Description & Justification: An emergency stopping mechanism shall be implemented between the vacuum module and electrical module to ensure that the turbomolecular pump does not break in case of a leak in the vacuum system. The turbomolecular pump is the most expensive single piece of equipment used in this project. If it were to break, it would be very difficult to complete this project, and likely lead to the failure of the project.	
Nature of Validation: Throughout the design phase, the team considered the various pressures that the turbomolecular pump would be operating under, and it was determined that there are many points which could cause damage to the pump if it was operated incorrectly. Thus validating the need for a stopping mechanism in the case where the pump is on when it shouldn't be.	
Nature of Verification: Before testing on the turbomolecular pump, the circuitry for the stopping mechanism was implemented on a simple circuit that used an LED. The circuitry was able to successfully toggle the LED on and off for the various test cases, where the data from the test cases was received directly from the pressure gauges. Unfortunately, a final test was not able to be performed on the turbomolecular pump and the entire vacuum system, so this requirement could not be completely verified.	

Requirement: P-REG-20 Detection System Radiation Shielding	**Requirement Source:** Project Team, York University Health and Safety Department
Requirement Type: Regulatory	
Description & Justification: The detection system module shall have it's own radiation shielding to ensure bit flips of the electric components do not corrupt the data being received. This is important since radiation has the potential to change the values being measured by electrical devices. If this happens, then the results from the experiment become useless.	
Nature of Validation: Throughout the design process, the project team calculated what intensity of radiation would be received at the detection system to ensure that the	

shielding is warranted. To the project team's surprise, it was found that the location of the detection system received no more than background levels of radiation due to the radioactive source. Thus, this requirement was no longer valid; however, it remains in the case that strong radioactive sources are used in future experiments.
Nature of Verification: By performing calculations throughout the design and using analysis tools throughout the design process, it was determined that levels of radiation at the location of the detection equipment would not exceed background levels. However, since the full system was not able to be installed, a final test could not be performed to actually determine the radiation received at the detection system, so this requirement could not be completely verified.

15.1.3 Unmet Requirement

Requirement: P-FUN-50 Instrument Assembly for Trapping	**Requirement Source:** Project Supervisor
Requirement Type: Functional	
Description & Justification: A containment unit shall be assembled around the trapping mechanism to store the trapped positrons, and release them upon deactivation of the trapping mechanism. This is the crux of the project; without a method for containing the trapped positrons, the project goal cannot be achieved.	
Nature of Validation: This requirement is directly necessary to achieve the goal of the project, thus the requirement is valid or else the project will not be able to succeed.	
Nature of Verification: Unfortunately, the project was not able to reach a state where the design or assembly of the trapping instrumentation could be verified. However, the project was very close to this stage, and this shall be the next step once the project team is able to work on this project again.	

Requirement: P-PER-10 Positron Trapping Duration	**Requirement Source:** Project Supervisor, Industry Stakeholders
Requirement Type: Performance	
Description & Justification: The trapping mechanism shall be able to trap positrons for a minimum duration of 10 seconds. This is the minimum duration for which positrons need to be held in order for them to either be useful in other engineering applications, or for study by physicists.	
Nature of Validation: During the design phase of the project, many research papers were consulted to confirm the duration of positron containment that would yield meaningful results. It was determined that for the amount of positrons that this system aims to capture, 10 seconds is the minimum duration for which they should be held, thus validating this requirement.	

Nature of Verification: Unfortunately, since the trapping and containment unit was not able to be assembled (see above verification), there was no way to analyze or test this requirement, and thus, it could not be verified.

Requirement: P-PER-30 Positron Trapping Duration	**Requirement Source:** Project Supervisor, Industry Stakeholders
Requirement Type: Performance	
Description & Justification: The minimum quantity of positrons trapped by the containment unit shall be at least 50,000 positrons per operation of the experiment. This is the minimum amount of positrons that the radioactive source that has been donated to this project should be able to supply, any less indicates a major deficiency in the system.	
Nature of Validation: Similar to the above requirement, many research papers were consulted during the design phase to determine what amount of positrons would be feasible given our system parameters. This coupled with papers that outline use cases and ways to study positrons allowed us to validate the 50,000 positron figure set in this requirement.	
Nature of Verification: Unfortunately, since the trapping and containment unit was not able to be assembled (see above verification), there was no way to analyze or test this requirement, and thus, it could not be verified.	

Requirement: P-INT-20 Lab Instruction Documentation	**Requirement Source:** Project Supervisor, York Physics Faculty & Students
Requirement Type: Interface	
Description & Justification: A instruction manual shall be created for the purpose of instructing future physics students on the procedure of setting up and conducting the experiment. This is required to ensure that the physics students who will be conducting this lab in future years are supplemented with the background information required to perform their lab.	
Nature of Validation: The physics students who aided with this project were consulted on the key aspects of the manual for each module of the project. Their input helped us create an overall design of the manual, while ensuring its purpose for instructing future students remains valid.	
Nature of Verification: This document was intended to be completed upon the completion of the experiment to ensure that procedure could be outlined well without any errors. Unfortunately, since the trapping and containment unit was not able to be constructed, this document also remains incomplete, and is thus unable to be verified.	

Requirement: P-REG-30 Containment Module Radiation Shielding	**Requirement Source:** Project Supervisor, Project Team, York University Health and Safety Department
Requirement Type: Regulatory	
Description & Justification: Radiation shielding shall be assembled around the containment module to ensure that radiation emitted from within does not exceed 1.8 milli Seiverts. In order to comply with the regulations set by the York University health and safety department, and to keep lab operators safe, the radiation shielding needs to be sufficient to prevent lab operators from getting a dose greater than standard background radiation. This value is 1.8 milli Seiverts.	
Nature of Validation: Similar to the radiation model requirement, throughout the design and conception phase, the project team met with York University's physics health and safety branch to confirm the regulations around radioactive materials for use in the project. From these meetings, the project team learned what the regulated standard value is, of 1.8 milli Seiverts, thus validating this requirement.	
Nature of Verification: A meeting had been scheduled with a representative from the physics health and safety department who would measure the radiation in the room after the radioactive source was installed. If the room was deemed safe by this representative, then this requirement would have been verified. Unfortunately, due to the Covid-19 pandemic, this meeting had to be cancelled, and this requirement remains unverified.	

Requirement: P-PRO-40 Positron Capture Verification	**Requirement Source:** Project Supervisor, Project Team
Requirement Type: Procedural	
Description & Justification: Upon completion of the entire system assembly, an experiment shall be conducted to ensure that the system is able to capture positrons. By doing this, the project team will be able to determine if the project goal has been achieved.	
Nature of Validation: The need for this requirement is a core component of this project. If the system is unable to contain positrons, then the main goal of the project cannot be achieved. Thus the need for this requirement stems from the goal of the project; to contain positrons.	
Nature of Verification: After operating the system for a short duration, the positrons should be in the potential well of the trapping mechanism. By decreasing the potential energy on one side of the trap, the positrons can be released towards the detection system to annihilate. If the detection system outputs a result similar to the results from the tests of the detection system, but scaled to account for the lesser positrons annihilating, then this requirement will be verified, and the project goal will have been achieved. Unfortunately, since the assembly of the containment unit was unable to be completed, this test was not able to be performed, and this requirement remains unverified.	

15.2 Appendix B - Work Packages

15.2.1 New Work Packages

To reflect a work package that has been newly added to the work breakdown structure, the ID has been altered slightly. New packages use a decimal followed by the number of the new package that represents the number of additions to the tree. Thus, an ID ending in XXX-Y.2 means it is the second work package after Y under the section XXX.

WP ID: DE-RSD-5.1	**WP Name:** Build solidworks model for radiation shielding
Worked Hours: 25	**WP Manager:** Yaseen **WP Support:** Mohammad
Required Inputs: 1.) Radiation shield component CAD files from MarShield 2.) Shielding assembly dimensions	
Work Package Tasks: 1.) Get material data from CAD files 2.) Assemble various CAD components of different radiation shielding pieces	
Work Package Outputs: 1.) Solidworks model of radiation shielding assembly	

WP ID: DE-RSD-5.2	**WP Name:** Perform analysis on solidworks model using radiation analysis tools
Worked Hours: 25	**WP Manager:** Yaseen **WP Support:** Akshay & Farshad
Required Inputs: 1.) Radiation shielding Solidworks model	
Work Package Tasks: 1.) Perform dose analysis on items outside of radiation shielding 2.) Determine minimum safe distance of operation **OR** 3.) Determine if radiation shielding is sufficient without extra precautions	

Work Package Outputs:
1.) Safe operation modes of the experiment

WP ID: DE-CSD-2-8.1	WP Name: Design electrode for collection system
Worked Hours: 40	WP Manager: Akshay WP Support: Mohammad
Required Inputs: N/A	
Work Package Tasks: 1.)	
Work Package Outputs: 1.) Electrode Design	

WP ID: DE-CSD-2-8.2	WP Name: Magnetic field design
Worked Hours: 40	WP Manager: Amara WP Support: Pruthvi
Required Inputs: 1.) Geomagnetic field measurements	
Work Package Tasks: 1.)	
Work Package Outputs: 2.) Magnetic field intensity and directionality at various locations in system	

WP ID: AS-VSA-2-10.1	WP Name: Turbomolecular and Roughing Pump Setup
Worked Hours: 30	WP Manager: Hunter, Kareem & Ashifa

	WP Support: Akshay
Required Inputs: 1) Small section of closed of vacuum assembly	
Work Package Tasks: 1) Configure the roughing and turbomolecular pumps for the small vacuum chamber 2) Run the roughing pump and bring the pressure in the system to 400 milli Torr 3) Run the turbomolecular pump and bring the pressure in the system to a high vacuum	
Work Package Outputs: 1) Assembly of vacuum pump apparatus	

WP ID: AS-CSA-2-14.1	**WP Name:** Magnetic Coil Assembly
Worked Hours: 30	**WP Manager:** Amara **WP Support:** Pruthvi
Required Inputs: 1) Magnetic coil design	
Work Package Tasks: 1)	
Work Package Outputs: 1) Assembly of magnetic coils around the vacuum equipment	

WP ID: TE-EFT-2-19.1	**WP Name:** Magnetic Coil Testing
Worked Hours: 20	**WP Manager:** Amara **WP Support:** Pruthvi
Required Inputs: 1) Magnetic coil Assembly	
Work Package Tasks:	

1) Test the assembled magnetic coils to ensure they produce the same magnetic field that was designed for.
Work Package Outputs: 1) Verification of the proper functionality of the magnetic coils.

15.2.2 Modified Work Packages

The following work packages are those that have been modified since the PDR. The original specifications have been left, with a clearly indicated modified version for each of the work packages. Modifications range from changing the managing party or duration of work to be spent on the work package, to changes in the required tasks for the work packages.

WP ID: DE-CRM-1-1	**WP Name:** Perform hand calculations for Our Lab Parameters
Worked Hours: 25	**WP Manager:** Mohammad & ~~Pruthvi~~ Yaseen **WP Support:** Kareem
Required Inputs: 1.) Lab Geometry 2.) Type/ Strength of Radioactive Source	
Work Package Tasks: 1.) Gather data required for calculations 2.) Determine areas of high radiative flux. 3.) Choose optimal locations for radiation shielding 4.) (*NEW) Determine required quantity of radiation shielding to order from MarShield	
Work Package Outputs: 1.) Locations for Radiation Shielding	

WP ID: DE-CRM-2-2	**WP Name:** Create Software for any input parameters for other lab setups
Expected Hours: 40	**WP Manager:** Hunter **WP Support:** Akshay & ~~Pruthvi~~ Ashifa
Required Inputs:	

1.) Radiation modelling algorithm
Work Package Tasks: 1.) Develop Software to automate the hand calculation process 2.) (Secondary) Enhance software to specify optimal locations for radiation shielding
Work Package Outputs: 1.) Software to determine areas of high radiative flux 2.) (Secondary) Software to determine optimal locations for radiation shielding

WP ID: DE-VD-1-3	**WP Name:** Design Emergency Stop Circuit
Worked Hours: 10	**WP Manager:** ~~Kareem~~ → Hunter **WP Support:** ~~Hunter~~ → Kareem
Required Inputs: 1.) Design specifications of turbomolecular and atmospheric pumps	
Work Package Tasks: 1.) Determine failure modes of pumps 2.) Design ways to detect failure modes 3.) Design circuit to stop pumps upon failure detection	
Work Package Outputs: 1.) Circuit schematic for turbomolecular pump shutoff	

WP ID: DE-VD-2-4	**WP Name:** Vacuum chamber & pathway design
Worked Hours: 20 → 40	**WP Manager:** Akshay ~~& Yaseen~~ **WP Support:** ~~Ashifa & Hunter~~ Mohammad & Pruthvi
Required Inputs: N/A	
Work Package Tasks: 1.) Design setup for vacuum assembly 2.) (*NEW) compare design against stockpile list to ensure required parts are available	

<table>
<tr><td>Work Package Outputs:
1.) Locations for the vacuum assembly
2.) (*NEW) List of parts that need to be ordered</td></tr>
</table>

<table>
<tr><td>WP ID:
DE-DSD-6</td><td>WP Name:
Detection System Design</td></tr>
<tr><td>Worked Hours:
40 → 20</td><td>WP Manager:
<s>Akshay & Yaseen</s> Kareem

WP Support:
<s>Mohammad</s> Hunter</td></tr>
<tr><td colspan="2">Required Inputs:
1) Outputs from Vacuum Chamber & Pathway Design (D-VD-2-4)</td></tr>
<tr><td colspan="2">Work Package Tasks:
1) Determine optimal locations (distance from positron beam & orientation) for photomultiplier tubes
2) Design connection circuit for multiple photomultiplier tube arrays
<s>3) Design timing circuit to detect concurrent photomultiplier tube triggers</s></td></tr>
<tr><td colspan="2">Work Package Outputs:
1) Locations for photomultiplier tube arrays
2) Circuit schematic for <s>photomultiplier tube triggering timer</s> detection system</td></tr>
</table>

<table>
<tr><td>WP ID:
DE-CSD-1-7</td><td>WP Name:
Nitrogen Gas Injection Module Design</td></tr>
<tr><td>Worked Hours:
25 → 30</td><td>WP Manager:
Pruthvi & <s>Ashifa</s> Akshay

WP Support:
<s>Kareem & Mohammad</s> Hunter & Mohammad</td></tr>
<tr><td colspan="2">Required Inputs:
N/A</td></tr>
<tr><td colspan="2">Work Package Tasks:
1) Determine volume of nitrogen gas required to slow positrons
2) Design Injection valve to deposit nitrogen gas in discrete quantities defined by the above volume.
3) Design Gas/Vacuum tube interface</td></tr>
<tr><td colspan="2">Work Package Outputs:</td></tr>
</table>

1) Mechanical design schematic for nitrogen gas injection system

WP ID: DE-CSD-2-8	**WP Name:** Detection integration design
Worked Hours: 10	**WP Manager:** Mohammad **WP Support:** Akshay
Required Inputs: ~~1) Output from nitrogen gas injection module design (D-CSD-1-7)~~ N/A	
Work Package Tasks: 1) Design collection system vacuum chambers to integrate with previous assembly of detection system. 2) Outline and document what components of the detection system need to be removed (if any)	
Work Package Outputs: 1) Documentation of changed components from detection design (if applicable)	

WP ID: TE-VAT-15	**WP Name:** Vacuum Assembly Testing
Expected Hours: 5 → 20	**WP Manager:** Akshay & ~~Yaseen~~ Hunter **WP Support:** Kareem & Ashifa
Required Inputs: 1) Vacuum pipe assembly (A-VSA-2-10)	
Work Package Tasks: 1) Ensure that a high vacuum is maintained in each section of pipe 2) Ensure that pipes are sealed and fastened together	
Work Package Outputs: 1) Verification of vacuum assembly	

WP ID: TE-RLT-17	**WP Name:** Radiation leak testing

Expected Hours: 5	**WP Manager:** N/A*** **WP Support:** ~~Mohammad & Kareem~~ Everyone
Required Inputs: 1) Output from detection system assembly (A-DSA-12)	
Work Package Tasks: 1) Consult with radiation safety workers in physics department to determine areas of setup that do not meet radiation safety standards 2) Correct any radiation leak issues and re-perform test	
Work Package Outputs: 1) Verification of no radiation leakage	

WP ID: TE-EFT-1-18	**WP Name:** Detection Equipment Initial Testing
Worked Hours: 5 → 10	**WP Manager:** Hunter ~~Ammara & Mohammad~~ **WP Support:** Kareem, Farshad & Ashifa ~~Ammara~~
Required Inputs: N/A	
Work Package Tasks: 1) Ensure photomultiplier tubes function correctly testing with light source 2) Ensure photomultiplier tubes can detect small photon packets 3) Identify poorly performing equipment 4) Implement accommodation strategy for poor equipment performance case (if applicable)	
Work Package Outputs: 1) Verification of detection equipment performance	

WP ID: TE-EFT-2-19	**WP Name:** Collection Equipment Initial Testing
Expected Hours: 5 → 40	**WP Manager:** ~~Hunter & Farshad~~ Mohammad & Yaseen **WP Support:**

	Kareem & Hunter
Required Inputs: N/A	
Work Package Tasks: 1) Test that generated electric field for penning trap meets design criteria 2) Test that generated magnetic field for penning trap meets design criteria	
Work Package Outputs: 1) Verification of collection equipment performance	

15.2.3 Unmodified Work Packages

WP ID: AS-VSA-1-9	**WP Name:** Implement Turbo-molecular pump emergency stop circuit
Worked Hours: 15	**WP Manager:** Kareem & Hunter **WP Support:** Ashifa & Mohammad
Required Inputs: 1) Output from emergency stop circuit design (D-VD-1-3)	
Work Package Tasks: 1) Implement emergency stop circuit 2) Run post implementation tests to confirm functionality works 3) (secondary) Implement emergency stop circuit for atmospheric pump	
Work Package Outputs: 1) Assembly & Implementation of emergency stop circuit for pump	

WP ID: AS-VSA-2-10	**WP Name:** Vacuum pipe assembly
Expected Hours: 15	**WP Manager:** Akshay & Yaseen **WP Support:** Hunter & Ashifa
Required Inputs: 1) Output from radiation shielding design (D-RSD-5) 2) Output from vacuum chamber and pathway design (D-VD-2-4)	

Work Package Tasks: 1) Assemble vacuum pipes together 2) Insert vacuum pipe assembly within designated areas for radiation shielding
Work Package Outputs: 1) Vacuum pipe and positron pathway

WP ID: AS-RSA-2-11	**WP Name:** Radiation Shielding Assembly
Expected Hours: 10	**WP Manager:** Ashifa & Yaseen **WP Support:** Mohammad
Required Inputs: 1) Output from radiation shield design (D-RSD-5) 2) Output from vacuum pipe assembly (A-VSA-2-10)	
Work Package Tasks: 1) Setup radiation shielding in marked locations around vacuum pipes	
Work Package Outputs: 1) Radiation shielding setup	

WP ID: AS-DSA-12	**WP Name:** Detection System Assembly
Worked Hours: 20	**WP Manager:** Kareem & Farshad ~~Mohammad~~ **WP Support:** Hunter
Required Inputs: 1) Output from vacuum pipe assembly (A-VSA-2-10) 2) Output from detection system design (D-DSD-6) 3) Output from detection equipment initial testing (T-EFT-1-18)	
Work Package Tasks: 1) Construct timing circuit 2) Implement timing circuit 3) Implement photomultiplier tube array at designated locations 4) Tune photomultiplier tube array	
Work Package Outputs:	

1) Detection system

WP ID: AS-CSA-1-13	**WP Name:** Nitrogen gas injection assembly
Expected Hours: 20	**WP Manager:** Pruthvi & Kareem **WP Support:** Hunter & Akshay
Required Inputs: 1) Output from nitrogen gas injection design module	
Work Package Tasks: 1) Prepare nitrogen gas storage area 2) Assemble injection module from design specifications	
Work Package Outputs: 1) Gas injection module	

WP ID: AS-CSA-2-14	**WP Name:** Collection Unit Assembly
Expected Hours: 20	**WP Manager:** Hunter & Akshay **WP Support:** Pruthvi & Kareem
Required Inputs: 1) Output from detection system integration design (D-CSD-2-8) 2) Output from nitrogen gas injection assembly (A-CSA-1-12)** 3) Output from collection equipment initial testing (T-EFT-2-19)	
Work Package Tasks: 1) Assemble positron trap according to the detection integration design Implement gas injection module when assembly is complete**	
Work Package Outputs: 1) Collection chamber with integrated gas injection	

WP ID: TE-VLFCT-16	**WP Name:** Vacuum leak failure circuit testing

Expected Hours: 5	**WP Manager:** Kareem & Hunter **WP Support:** Ashifa & Mohammad
Required Inputs: 1) Output from turbomolecular pump emergency stop circuit implementation (-VSA-1-9)	
Work Package Tasks: 1) Test circuit triggers when pressure gauge goes above desired threshold 2) Test circuit triggering functions correctly and stops pump 3) Test failure mode where increase in pressure within vacuum pipes toggles turbomolecular pump	
Work Package Outputs: 1) Verification of emergency shutoff circuit	

WP ID: TE-VT-1-20	**WP Name:** Positron Detection Verification
Worked Hours: 15	**WP Manager:** Akshay & Pruthvi **WP Support:** Hunter
Required Inputs: 1) Output from detection system assembly (A-DSA-12)	
Work Package Tasks: 1) Operate system in detection mode 2) Verify positron annihilation results in photomultiplier tube producing a current 3) Determine locations of failure resulting in no detection (if applicable) 4) Address issues and reperform test (if applicable)	
Work Package Outputs: 1) Verification of positron flux into containment unit	

WP ID: TE-VT-2-21	**WP Name:** Positron Capture Verification
Expected Hours: 15	**WP Manager(s):** Akshay & Farshad

	WP Support: Ammara & Hunter
Required Inputs: 1) Output from collection system assembly (A-CSA-2-14)	
Work Package Tasks: 1) Operate system in capture mode 2) Collect positrons for 20 seconds 3) Release positrons in controlled annihilation 4) Verify annihilation results are from multiple positrons 5) Determine locations of failure resulting in minimal/no capture (if applicable) 6) Address issues and reperform test (if applicable)	
Work Package Outputs: 1) Verification of positron containment resulting in project success	

WP ID: TE-UAT-22	**WP Name:** User Acceptance Testing
Expected Hours: 10	**WP Manager(s):** Kareem & Ashifa & Farshad **WP Support:** Pruthvi, Ammara
Required Inputs: 1) Output from positron capture verification (T-VT-2-21)	
Work Package Tasks: 1) Meet with stakeholders and perform demo of project 2) Receive and document feedback 3) Fix issues that arise from user testing, and repreform test with same user group until there are no more issues	
Work Package Outputs: 1) Verification that stakeholder requirements are met	

WP ID: DC-TPD-23	**WP Name:** Tuning parameters determination
Worked Hours: 10	**WP Manager:** Hunter & Mohammad **WP Support:** Pruthvi & Ashifa

Required Inputs: 1) Output from positron capture verification (T-VT-2-21)
Work Package Tasks: 1) Operate system in capture mode with different inputs and collect data on positron capture 2) Collect data to determine the optimal system parameters which result in the most positrons captured
Work Package Outputs: 1) Optimal configuration of system parameters

WP ID: DC-PRD-24	**WP Name:** Performance Rating Determination
Expected Hours: 5	**WP Manager:** Ammara & Ashifa **WP Support:** Akshay
Required Inputs: 1) Output from tuning parameter determination	
Work Package Tasks: 1) Operate system in capture mode and collect data 2) Repeat to determine a statistical mean value and standard deviation for positrons captured by system 3) Compare results of positron detection system with other antimatter containment designs to rank system	
Work Package Outputs: 1) Performance determination relative to other state of the art containment methods	

WP ID: LD-LDS-25	**WP Name:** Lab Safety Documentation
Expected Hours: 10	**WP Manager:** Farshad & Ashifa **WP Support:** Hunter
Required Inputs: N/A	
Work Package Tasks:	

1) Create safety manual for operating the antimatter containment unit 2) Review safety manual with project supervisor 3) Apply changes requested from project supervisor(if applicable)
Work Package Outputs: 1) Safety Manual

WP ID: LD-HOSD-26	**WP Name:** Hardware operation and setup documentation
Expected Hours: 10	**WP Manager:** Hunter & Ashifa **WP Support:** Kareem
Required Inputs: N/A	
Work Package Tasks: 1) Create experiment operation manual 2) Create hardware setup manual 3) Review manuals with project supervisor 4) Apply any changes requested from project supervisor (if applicable)	
Work Package Outputs: 1) Experiment Operation Manual 2) Hardware Setup Manual	

WP ID: LD-SOSD-27	**WP Name:** Software operation and setup documentation
Expected Hours: 10	**WP Manager:** Hunter **WP Support:** Ashifa
Required Inputs: N/A	
Work Package Tasks: 1) Create software operation and setup manual 2) Review software operation manual with project supervisor	

3) Apply any changes requested from project supervisor (if applicable)
Work Package Outputs: 1) Software Operation Manual

WP ID: LD-SED-1-28	**WP Name:** Lab Instruction Documentation
Expected Hours: 10	**WP Manager:** Ammara **WP Support:** Farshad & Akshay
Required Inputs: N/A	
Work Package Tasks: 1) Create physics lab instruction document 2) Review instruction document with project supervisor 3) Apply any changes requested from project supervisor	
Work Package Outputs: 2) Lab instruction Manual	

WP ID: LD-SED-2-29	**WP Name:** Lab Information Documentation
Expected Hours: 10	**WP Manager:** Ammara **WP Support:** Farshad & Akshay
Required Inputs: N/A	
Work Package Tasks: 1) Create lab background information document 2) Review information document with project supervisor 3) Apply any changes requested from project supervisor	
Work Package Outputs: 3) Lab Information Document	

15.3 Proposals sent - External/Internal

Antimatter Containment Unit:

Proposal for Kurt J. Lesker Company

About Project

The Antimatter Containment Unit is a project pertaining to the trapping of anti-electrons or positrons within an experimental setup. The project is a collaboration with the Physics Department and the Lassonde School of Engineering with a team of six engineering and three physics students. The project has immediate potential for impact as a base for graduate level research, as well as an undergraduate physics laboratory course at York University. Additionally, there will be an online course, targeted to undergraduate and graduate students but also available to anyone with interests in antimatter, the physics behind it or vacuum systems. The final report will be posted on York University's Institutional Repository called York Space. This repository is on the official York University website and mostly used by researchers, but also available to the general public.

Background and Vision

The study of antimatter has puzzled scientists since its discovery in the 1930's. In the field of physics every type of particle has its own antiparticle, the only difference being that an antiparticle has an opposite electric charge compared to its counterpart. It is this antiparticle, that we refer to as 'antimatter'. Experiments at CERN, such as "The Antihydrogen Trap (ATRAP) project in collaboration with York University and many other institutions, seek to collect and study antimatter in a way that has never been done before. Because of the enigmatic nature of this phenomenon, antimatter research is globally funded. One of the more prominent mysteries surrounds the asymmetry of its existence. When the Big Bang occurred, it should have created equal amounts of matter and antimatter. However; this was not the case, as there is far more observable matter than antimatter in the universe, which is what drives research. Due to its volatile nature, without a storage mechanism, antimatter annihilates upon contact with matter. To gain a more profound understanding, research requires a controlled method to store antimatter, so that it can be studied to a greater extent. For examination usage, antimatter needs to be collected and trapped for extended periods of time. And so, our team at York University has set out to do just that – trap antimatter.

Project Deliverables

By referencing previous projects on antimatter containment like the ATRAP experiment done at CERN along with our own research, we have come up with an experimental setup, that will aim to moderate, and trap positrons being emitted from a radioactive source.

The project has two distinct objectives that count towards its success. The first is the detection of the positrons being emitted. Detection is key in determining the quality of performance of the final containment unit, since we need to be able to detect positrons to determine the total positron containment potential. The second objective is the actual trapping of the positrons through the implementation of a hybrid buffer gas and penning trap. A successful implementation of the trapping mechanism will mean that positrons at certain energy levels will be able to be contained for a specific period of time. In totality, a vacuum system assembly coupled with a radiation source and shielding, precisely designed magnetic and electric fields, and a nitrogen gas injection module is to be fabricated as the main deliverable for this project with a delivery date of April 30th, 2020.

Our Ask

As mentioned above, this project is a York University collaboration between Lassonde School of Engineering and the Physics Department. The physics dept has donated most of our project equipment. The experimental setup is designed to make use of as much donated equipment as possible. However, we are still in need of equipment that is essential for the completion of our project. To fill in this gap, we are seeking a sponsorship from Kurt J. Lesker Company to help us in achieving this goal.

Sponsorships can be in the form of

- Monetary Donation - the goal to meet is $10,000 for the purchase of all the required equipment (including lead radiation shielding)

OR

- Product Donation
  - Vacuum system parts and accessories
  - Radiation shielding (lead)

What we offer

By sponsoring this project Kurt J. Lesker Company will receive brand exposure in the following ways:

- Logo being included in all documentation - reports, posters, brochures and presentations. The final report will be posted on York Space
- Sponsorship recognition at Capstone Exhibit Day Presentation. Capstone Exhibit Day is on April 30th at York University where all teams will come together to present their

projects to both faculty and industry professionals. Below is a breakdown of those that will be invited

- 14 External Project Partners from various industries
- 31 Faculty Project Supervisors
- 31 External (Industry) Project Advisors
- 7 Faculty Deans from 7 different faculties, including the Lassonde School of Engineering
- 3 Organizations; PEO, AWOL, Carswell

- Sponsorship recognition in all press releases done both online and offline
  - Includes logo being included within the project video which will be shared online
- Fostering a relationship with the Physics and Engineering departments at York University for future projects
- Publishing the project on your own company website
- And anything else that you as the sponsor may have in mind

Upon success, this will be the first antimatter trap built by undergraduates in North America. We would love for you to be a part of this and help us achieve what we have set out to do.

The entire AMCU team would like to thank you for your time and consideration in supporting this project.

Sincerely,

Antimatter Containment Unit team 2020

Antimatter Containment Unit:

Proposal for the Lassonde School of Engineering

About Project

The Antimatter Containment Unit is a project pertaining to the trapping of anti-electrons or positrons within an experimental setup. The project is a collaboration with the Physics Department and the Lassonde School of Engineering with a team of six engineering and three physics students. The project has immediate potential for impact as a base for graduate level research, as well as an undergraduate physics laboratory course at York University. Additionally, there will be an online course, targeted to undergraduate and graduate students but also available to anyone with interests in antimatter, the physics behind it or vacuum systems. The final report will be posted on York University's Institutional Repository called York Space. This repository is on the official York University website and mostly used by researchers, but also available to the general public.

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Potential Impact

This project, upon its successful completion, will be the first antimatter trap built by undergraduate students in North America. The exposure that Lassonde will get from the success of this project is immeasurable. We are not just competing against local projects but rather all the ones that are in progress currently across Canada. There are only a couple of capstone projects which surface every year due to their differentiating factor from all over Canada. Those that strive to be the first to accomplish a difficult undertaking are remembered without effort and so we have the opportunity, mindset, and experienced faculty support to be one of those projects this year. Through this project we want to showcase the Lassonde School of Engineering to the rest of Canada in the best way possible.

A case in point

Concordia University Electron Accelerator - Mini Electron Gun Accelerator 2012

In 2012 a team of Mechanical Engineers from Concordia University designed and built an electron accelerator for their Capstone project. Their success made this the first particle accelerator made by undergraduates in Canada and they did so within 220 days. In order to make this project a reality they raised $25,000 internally through Concordia and externally via sponsorships. Their story was covered on all major media outlets in Montreal including The Montreal Gazette and CBC Montreal. Along with that, TRIUMF (Canada's national particle accelerator centre) who also was one of their sponsors shared the story on their website. The project was then displayed at the Canadian Undergraduate Tech Conference in Toronto while also being selected by Concordia University to represent the university at the 2012 international congress of the Canadian Society of Mechanical Engineering. The team was also invited to the Canadian Light Source which is home to one of the biggest particle accelerators to demonstrate the project and tour the facility.

All of this came from one project that these students undertook and were determined to complete. Below are links to some of the media coverage that the project received.

Relevant Media:

TRIUMF, April 2, 2012

CBC Montreal programs, April 9, 2012

Youtube Video Montreal Gazette, April 17, 2012

Montreal Gazette, April 18, 2012

Designcot, April 20, 2012

Our Ask

As mentioned above, this project is a York University collaboration between Lassonde School of Engineering and the Physics Department. The physics dept has donated most of our project equipment. The experimental setup is designed to make use of as much donated equipment as possible. However, we are still in need of equipment that is essential for the completion of our project. To fill in this gap, we are seeking a sponsorship from Lassonde to help us in achieving this goal. Our ask is for permission from Lassonde to spend (up to) $10,000 as needed towards the completion of this project (equipment purchases e.g. lead radiation shielding) – with the understanding that any other sponsor resources and funding are used before Lassonde's sponsorship towards this project. Currently, we are in conversation with 2 potential external sponsors but due to the limited time on our hands, we request this authorization from Lassonde so that we are able to move forward in our building process and meet our April 30th, 2020 deadline.