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Design and Construction of a Multi-Wire Proportional Chamber for Cosmic Ray Muon Detection

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Abstract

The Society of Physics Students (SPS) at Kennesaw State University is developing a low-cost modular multi-wire proportional chamber (MWPC) to detect muons from cosmic rays. The ultimate goal of the project is to deploy an array of chambers for muography, the three-dimensional density mapping of large structures using data from cosmic ray muon absorption. Although the basic technology of MWPCs was developed many years ago, MWPCs are typically large and expensive. So, they are only available to large laboratories, not to students. A secondary goal of this project is to develop a small, low cost MWPC that could be used in undergraduate lab classes to introduce students to the field of particle physics. The MWPCs the SPS is working on are 8’’ by 8’’, and consist of a 3D printed, plastic frame with copper and gold-plated tungsten wires sandwiched between two copper plates. The copper plates are at ground potential, and there is a potential difference of 2,000V between the two types of wire. Muons, which are negatively charged, pass through the chamber and ionize the gas inside. This starts an avalanche of electrons, which causes a current in one of the high voltage wires and sends a signal to the data collection equipment. The SPS has built a chamber that meets all the basic requirements of an MWPC.

Keywords: Cosmic Rays, Muography, Multi-Wire Proportional Chamber

1. Introduction

Multi-wire proportional chambers (MWPCs) can be used to measure cosmic-ray muon flux[1]. The MWPCs in this project consist of a set of wires between two grounded plates. There is a potential difference of approximately 2000V between neighboring wires, and the chamber is filled with argon/CO_2 gas. Since muons are electrically charged, high energy muons can ionize a gas molecule. In regions where the electric field is strong enough, this can start an avalanche of ionizations. If that happens, electrons released in the avalanche rush to a nearby high potential wire, causing a small current which can be amplified and recorded[2,3].

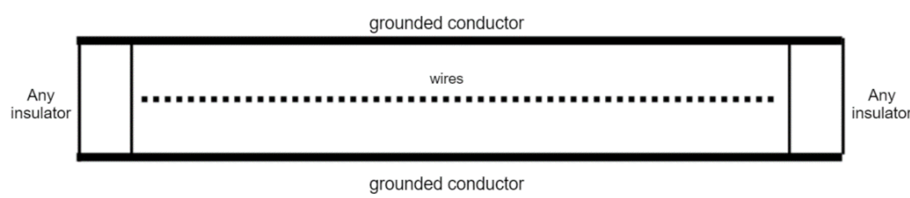

Figure 1. A drawing of a cross-section of a basic MWPC, viewed parallel to the wires’ axes.

There are two main goals of this project. The first is to build MWPCs that are cheap enough to be accessible to undergraduate labs, that can be built with readily available materials in a few hours, and that are modular, meaning that many small chambers could be connected to create the desired detection area. The second is to build an array of chambers and use them to do muography. Muography uses cosmic ray muon flux to create a three-dimensional density map of a large structure while being completely non-invasive[1]. The target structures for this project are the Etowah Indian mounds in Cartersville, GA.

This paper contains the design specifications for all of the pieces, lists all of the materials used, and gives directions for construction of the chambers in this project.

2. Chamber Construction

2.1. The Frame

The sole purpose of the frame is to provide structure for the wires and electronic components. On two opposite sides, the frame has a shelf to attach the printed circuit boards (PCBs), and 53 tiny grooves, each 3mm apart, to hold the wires in place. It also has a groove on both the top and the bottom to accommodate a 1/8" O-ring, and two 1/3" holes on one side so that it can be filled with gas. The two tall sides are 20mm high, ignoring the O-ring groove. The shorter edge of the shelf is 5mm high, while the tall edge is 10mm high. The shelf is 185mm long. The wire grooves are 1mm deep and 1mm in diameter.

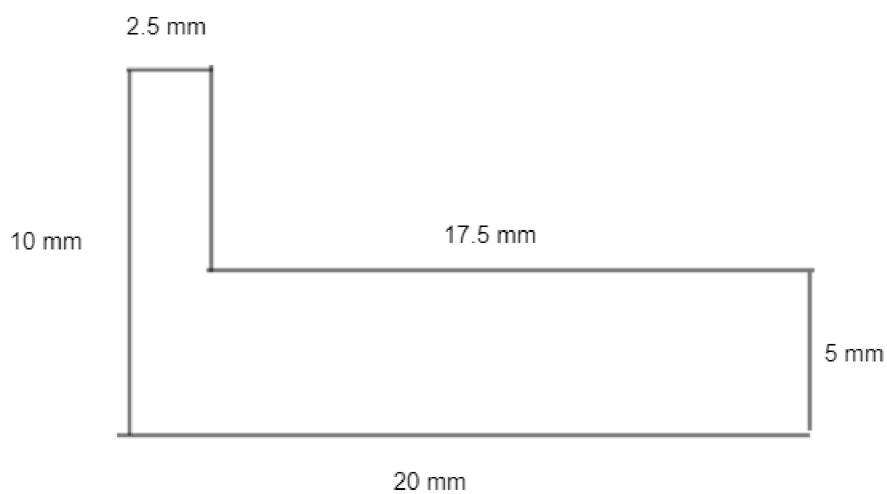

Figure 2. A drawing of the shelf's cross-section. The wires come in from the top left, and the PCB is glued on to the 17.5mm flat space. The O-ring groove was omitted from the bottom of the drawing for clarity.

For this project, the cheapest and most efficient way to obtain a frame is to 3D print it. Since 3D printing allows for the user to set the infill, the frame can be printed with just enough material to reach the desired rigidity with little waste. In addition, the frame can be completely customized to fit the desired size, wire spacing, etc.

The frame was designed in SolidWorks, a computer-aided design program that is commonly used in mechanical engineering. The SolidWorks design was then saved as an STL file, put through Cura, a 3D printing software that converts it to GCODE, and loaded onto the SD card that goes with the printer. The printer used is an Ultimaker 2 Extended+, and the frame was printed using polylactic acid (PLA), a biodegradable plant-based plastic. The frame is 205mm x 205mm square, and the usable detection area is 185mm x 185mm because the sides are 20mm thick. These dimensions were chosen because the print bed could not accommodate a much larger area than 205 x 205mm. The print takes approximately 10 hours on the printer's default speed and is done with a 0.4mm nozzle and 18% infill. Due to the size and shape of the frame, it was necessary to print at a lower speed than the default speed in order for the printer to print the sides near the edge of the print bed correctly, making the print approximately 15 hours.

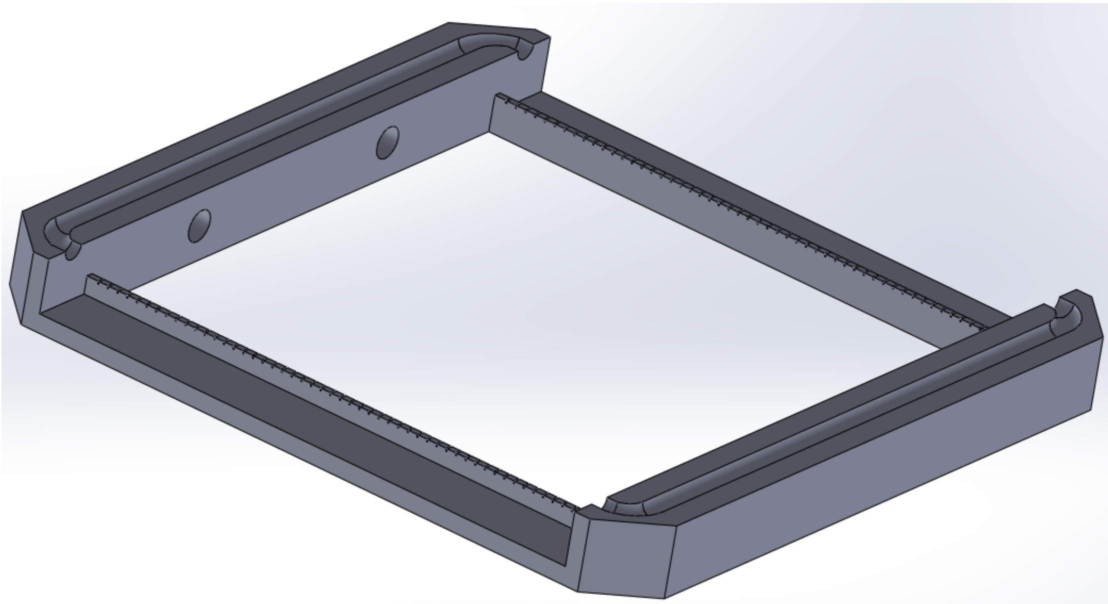

Figure 3. A screenshot of the model for the frame in SolidWorks

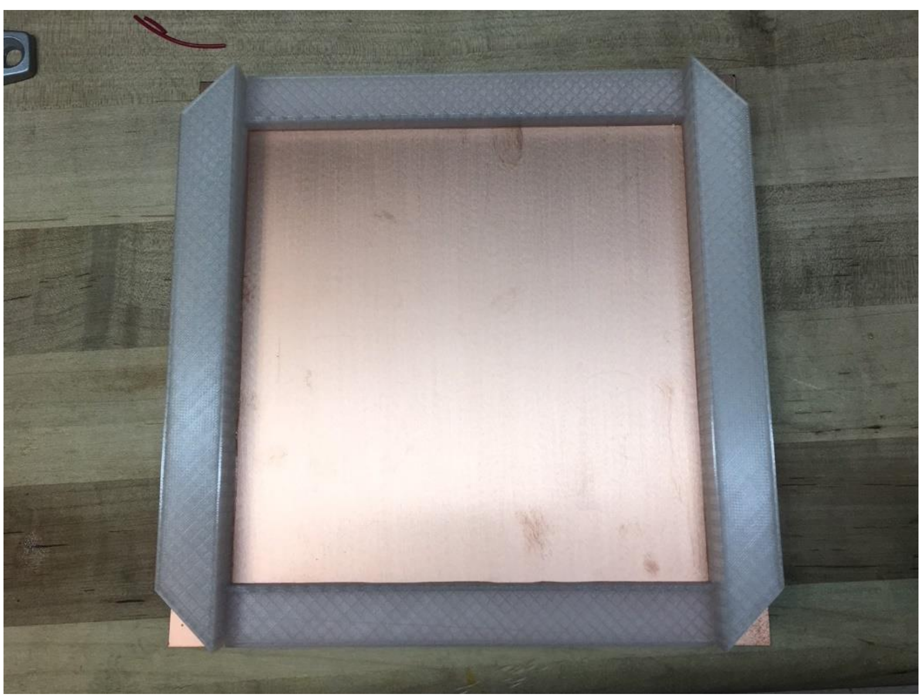

Figure 4. A 3D printed frame on top of a copper sheet. This prototype was from before O-rings were being used, so this one was intended to be sealed with glue.

2.2 Wiring

Once the frame is complete, the PCBs are glued into place, one on each side. Each PCB has small solder pads for the wires and etching that connects the ground wires to ground, supplies power to the high voltage wires, and connects each high voltage wire to a separate output. It is important for the chamber to be an open circuit[2], so extreme care is taken to ensure that there is no contact between high voltage wires. The PCBs are 1.65mm thick and were custom designed for this project to fit the shelf on the frame and have the correct wire spacing.

Figure 5. A close-up of one of the PCBs. The grooves on the frame can also be seen in this picture. The solder pads labeled “field” go to the ground wires, and those labeled “sense” go to the high voltage wires.

The wires are soldered onto the PCBs by hand, using a small weight on one end to hold them under tension until the solder cools. To attach a wire, one end is soldered on to the solder pad of the PCB and the wire is stretched across the chamber, making sure that it lays in the correct grooves on both sides. Then the weight is hung from the free end while that side is soldered down. After a few seconds, the solder is cool and the weight can be removed and used for the next wire, so only one weight is required to wire a chamber. The wiring process takes 2-3 hours.

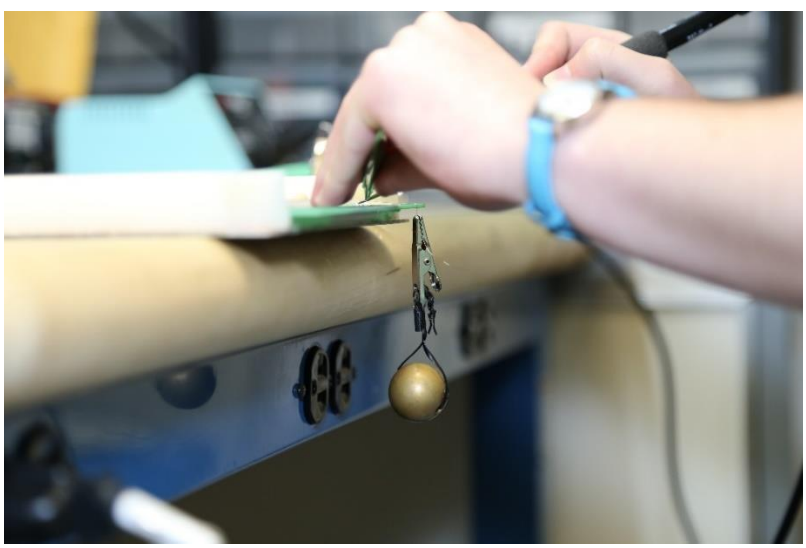

Figure 6. The weight hanging off the end of a wire while it is soldered on to the PCB. This picture is of soldering a copper wire and was taken before the discovery that copper wires deform.

Originally, it was intended that 100-micron diameter copper wires would be the ground wires, and 25-micron diameter gold-plated tungsten wires would be the high voltage wires. However, it was discovered that the copper deforms too easily when subjected to the strong electric field inside the chambers. Due to their opposite polarity, the copper wires and the gold wires were attracted to each other, causing the copper wires to stretch towards the gold ones. The gold wires were strong enough not to deform. New chambers will be constructed using only gold-plated tungsten wire. The weight used for tension on the gold-plated tungsten wires has a mass of 18 grams, meaning that they are under a tension of 0.176N [2].

The gold-plated wire was chosen because it is the wire typically used for MWPCs[2], and the diameter was chosen because it was the smallest that could reasonably be handled. Because of the nature of the electric field around a charged wire, using a smaller diameter wire means that a greater percentage of the chamber volume has a strong enough field for an avalanche[2].

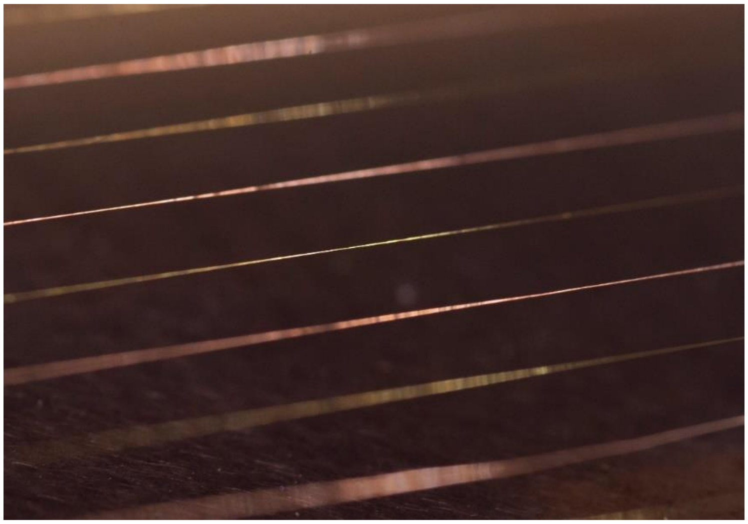

Figure 7. A close up of some wires that have already been attached. This picture was taken before the switch from copper and gold-plated tungsten to only gold-plated tungsten wire. It can be seen that the copper wires are already deformed, even though the picture was taken before any voltage was applied.

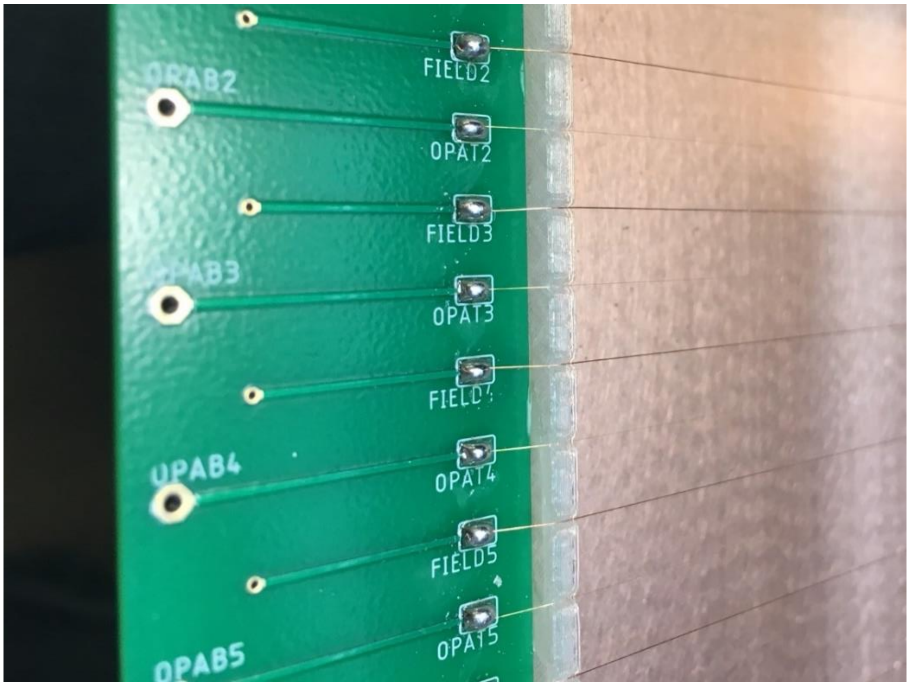

Figure 8. A close-up of one side of the PCB with wires attached. The wires labeled OPA (short for operational amplifier) are the high voltage wires, because this is the side of the chamber that was intended to be connected to the signal detection electronics. This picture was also taken when the copper wires were still in use.

2.3. Sealing

As stated previously, it is important that the chamber is an open circuit, so prior to sealing the chamber, any loose ends of wire are removed, and all of the solder joints are painted with an insulating varnish. This is to prevent any sparks that might happen on the edges of the chamber. The most efficient way to remove the loose ends of wire is to use a pair of tweezers to move the end back and forth until the wire breaks off at the solder joint. Wire cutters do not get close enough to the solder joint to remove all of the extra wire. In figure 7 above, the loose ends have already been removed.

Next, two more 3D printed pieces are added on top of the PCBs to protect the solder joints. They are smaller, so both can be printed at the same time. They are also printed with 18% infill and it takes approximately 5 hours to print both pieces. These pieces have to be glued on, meaning that broken wires can no longer be repaired. Then the O-ring is attached to the frame. It is intended that the pressure between the copper plate and the O-ring will make the chamber airtight. Several different O-ring materials and diameters have been tried, with mixed success. It was found that O-rings that had a smaller diameter and were made of softer material made a better seal. This is because the copper plates are not strong enough to put a decent amount of force on the O-ring without deforming. When sealed using screws on each of the corners, the copper plate bowed out in the middle of each of the sides. So, space for screws was added along the two solid sides, but because the sides containing the PCB cannot accommodate screws, this was not an effective solution. The current frame accommodates a 1/8" O-ring, and a search is being conducted for a better material.

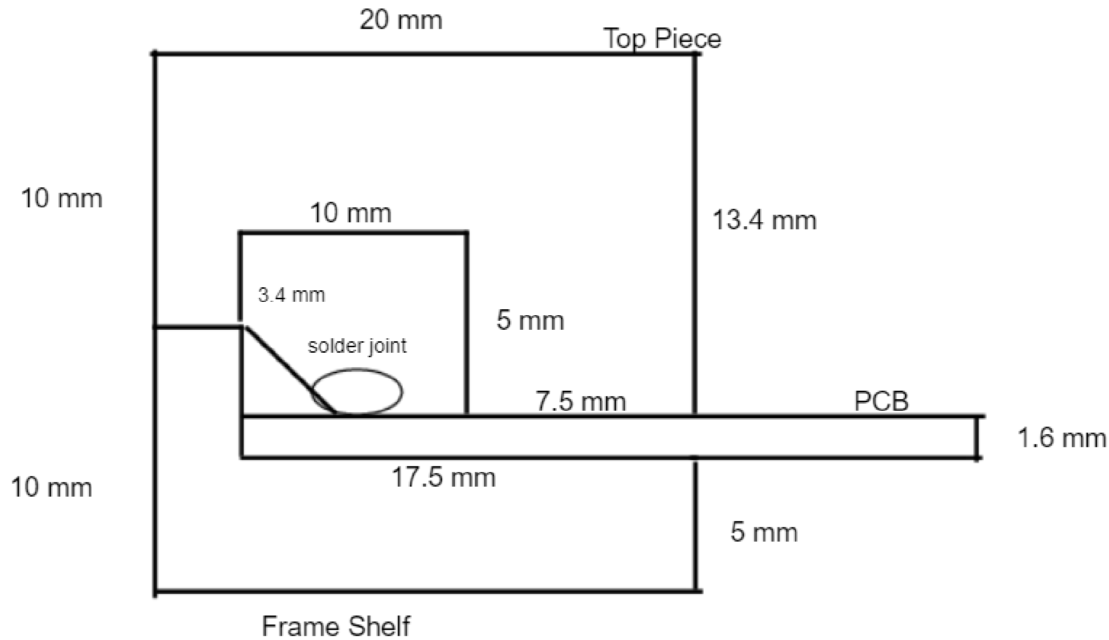

Figure 9. A cross-section of the part of the frame that holds the wires.

The bottom piece of figure 9 is the shelf pictured in figure 2 and the PCB is attached to it as pictured in figures 5 and 7. The wires come in from the left and the solder joint is completely enclosed by the frame pieces. The top of the top piece is level with the top of the tall sides of the frame pictured in figure 3 so that the top of the chamber will be flat when sealed. The PCB hangs off the edge so that it can be connected to the high voltage source and signal detection electronics. The O-rings and their grooves should be on the top and bottom edges of the square but were omitted from this drawing for simplicity.

At this stage of development, the chambers do not need to be perfectly airtight provided that the rate that gas is lost is near the rate that gas is put in. In addition, during testing the ability to open the chambers is more important than having a perfect seal. This allows for broken wires to be clipped off, although not repaired as mentioned above, and it allows for the chambers to be tested with other radioactive sources to establish functionality. Currently, the chambers are sealed with clamps around the edges.

Once a passible seal is achieved, the chamber is filled with Argon and Carbon Dioxide gases, in an 80:20 ratio. Although better gases could be used, Argon/CO_2 is a common welding gas that is cheap and easily obtainable. It was decided that the cheapness and availability outweighed any other benefits, at least during testing. In addition, Argon/CO_2 is consistent with other MWPC designs[2].

It should be noted that the copper plates are square, while the frame is a square with the corners cut off. This means that when the chamber is sealed, the corners of the copper plates hang over the edge. The exposed corners are connected to the ground input on one of the PCBs so that the plates will be grounded as well. This is accomplished by soldering one end of a small wire onto the exposed copper and the other end to the PCB. At this point, an amplifier and signal detection electronics can be attached to the chamber. Currently testing is being done with the AD 8099 operational amplifier in both single stage and two stage configurations.

Once voltage is applied, the chamber should be considered fully functional and is ready for signal testing.

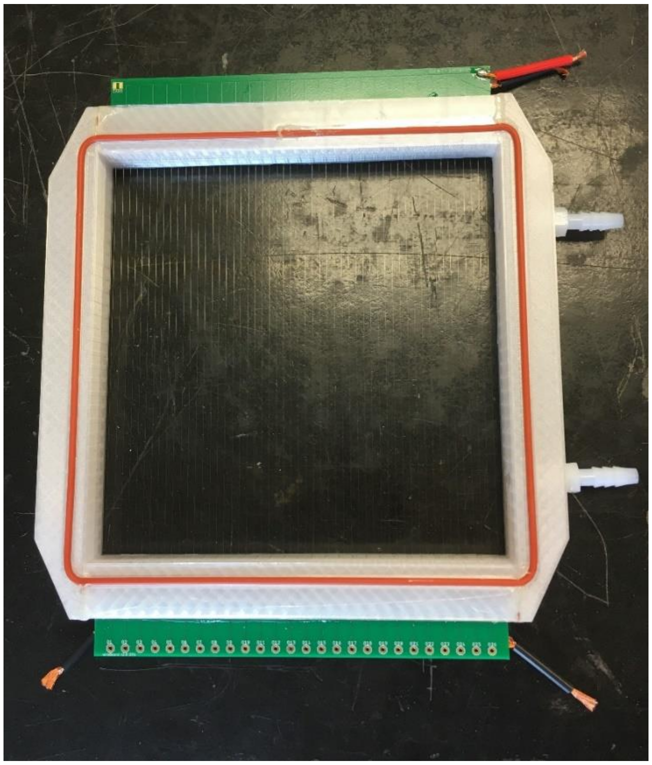

Figure 10. The most recent version of the chamber, without the copper plates on it.

3. Future Work

Currently a new chamber is being constructed with only gold-plated tungsten wires. This chamber will be tested with a beta source to establish functionality and optimize the electronics. If that is successful, then testing will be done to determine if the chamber can detect cosmic ray muons. Cosmic ray muon testing will include testing the chamber at different angles and elevations, and comparing the data taken to published data on cosmic rays.

4. Acknowledgements

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5. References

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