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Design, Testing, and Operation of Modular Multi-Wire Proportional Chambers for Cosmic Ray Muon Detection

Michael Z. Reynolds
Physics
Kennesaw State University
1100 South Marietta Pkwy
Marietta, GA 30066

Faculty Advisor: Dr. David Joffe

Abstract

The Student Physics Society (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. These chambers must undergo rigorous testing before they can be deemed functional. Each chamber must be able to hold stable high voltage with a magnitude of 2-3kV without leaking any current, which is not a trivial task. Each chamber must be able to hold gas at slightly above atmospheric pressure with no leaking, and each chamber must be able to transmit a pulse with minimal noise or distortion. When designing chambers to pass these tests, we must do so such that they can be constructed quickly, cheaply, and efficiently. The chambers must also be modular, which has several distinct advantages to traditional chambers—including flexibility in the size of the detection area, and the ability to quickly replace broken chambers without loss to resolution or functionality. This contribution to MWPC instrumentation will place into reach areas of physics to undergrads normally reserved for graduate students. Once a chamber has passed the three tests, our methodology then places the chambers under various methods of detecting the signal. The signal is acquired by the ionization of gas as a charged particle passes through the chamber. Primary ionization triggers secondary ionization, which then dumps charge on the anode wires that induces a small, detectable current. We are presently utilizing network analyzers, oscilloscopes, and simulations to help identify the signal. Once the signal is seen, we can shape it and begin the next stage towards muography.

Keywords: instrumentation, particle detector, cosmic ray muons

1. Introduction

The multi-wire proportional chamber (MWPC) was invented in 1968 by French-Polish physicist Georges Charpak during his time at CERN. His invention changed the game for particle physicists by vastly improving detection rates and precision by orders of magnitude[1]. Prior to the MWPC the primary method of particle detection was via cloud chambers or bubble chambers. These types of detectors created a physical track that needed to be photographed to be studied, which imposed severe limitations on speed, precision, and detection rate; these methods also made it difficult to reset the experiment for multiple trials.

Multi-wire proportional chambers have an electronic readout, which allows physicists to analyze interactions and particle paths on a computer. The rate of detection was increased from just a couple interactions per second to a thousand per second or more, and spatial resolution was vastly improved.

1.1 Purpose

There are two primary reasons for this project: economy and education. Typically, these types of chambers are large, bulky, relatively expensive, and difficult to construct. This project seeks to design a MWPC that is cheap, efficient, simple, and modular.

A *cheap* MWPC would be accessible to construct on a small department budget, funds raised by a student club, or a start-up company's limited capital. An *efficient* MWPC is characterized by construction materials that are readily available and easy to obtain, and when possible environmentally friendly. A *simple* MWPC is one that is not difficult or complicated to construct. Basic soldering skills and use of simple shop tools is all that is necessary. These chambers could be constructed by a couple of undergraduate students. Finally, a *modular* MWPC is one that is compact enough that many of them can be linked together to create an array of any detection area size or shape needed. This also means they are able to be taken from one location to another with little breakdown and set up.

Education is also an important aspect of the project. Typically, particle detectors are not first introduced until graduate school. This project aims to bring the construction techniques, function, operation, and theory of charged particle detection down to the undergraduate level.

2. Theory

A wire chamber is a gaseous detector that operates on ionization events like cloud chambers[2] and bubble chambers[3] do. But unlike these predecessor detectors, wire chambers do not create a visible path of ionization. Instead, ionization events dump charge on the anode wires via an electron avalanche. This charge travels down the anode wire in the form of an electronic pulse, which is detectable by the readout electronics.

Inside the sealed chamber are an array of anode wires stretched across the detection area, each a fixed distance from each other. The top and bottom planes of the detector are cathode plates whose purpose is to collect the ions that drift away from the anode wires. The chamber is filled with an inert gas mixture, often argon or neon in high proportion, and atmospheric pressure (or just slightly above).[4] High voltage is applied to the anode wires, usually in the range of 1kV to 2kV, while the cathode plates remain at ground potential. Polarity can be reversed with high negative voltage on the field shaping wires and zero volts on the anode wires. The electric field remains the same.

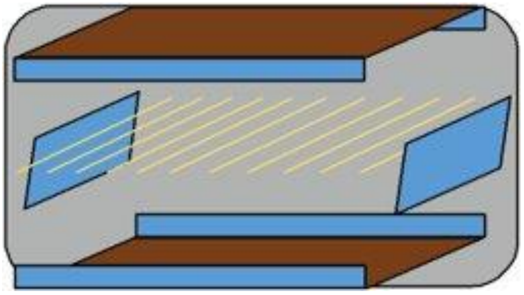

Figure 1. An exploded view illustration of a basic MWPC. The yellow lines are the wire array, the brown planes are the cathode plates, and the blue rectangles are non-conductiong frame material.

As an energetic, charged particle passes through the detection area it will initiate the primary ionization of gas molecules inside. Near enough to the anode wire the freed primary electrons will be fiercely attracted to the high voltage, and rush towards the anode wires triggering secondary ionization of the gas molecules.[5] This cascade effect amplifies exponentially until the avalanche reaches the anode wire inducing a pulse. The pulse reaches the readout electronics and is observed by the data collection system to be stored for computer analysis.

Since each wire has a dedicated readout the pulse indicates the wire near which the charged particle passed. If two chambers are stacked perpendicularly to each other, then the combined grid of wires represents an *x-y plane* and position information can be obtained since the distance between the anode planes is known. Further if four chambers are stacked mutually perpendicular to each other, then trajectory information can be obtained between the two observed points (one for each set of chambers) including angle of incidence. This information is useful for doing muography, particularly on large archeological or geographical structures.[6]

2.1 Townsend Avalanche

The process governing the electron avalanche by gaseous ionization was first described by John Sealy Townsend with his work at Cambridge (circa 1897), thus the phenomenon carries his name as a *Townsend avalanche*. Free electrons must carry just enough energy for ionization to occur from impact with gas molecules and induce an avalanche.[7] Two important factors that affect this impact ionization are electric field strength and mean free path.

Electric field strength is simply the magnitude of electric field that the electron experiences when freed from a gas molecule. If this field strength is too low, then the electron doesn't acquire enough energy to cause ionization. If the field strength is too high, then the breakdown voltage may be reached, and ionization is sustained (continuous discharge). Mean free path is the average distance between collisions. If the mean free path is too short, then the electron loses energy in non-ionizing collisions. If the mean free path is too long, then the electron reaches the anode before any collision can occur.

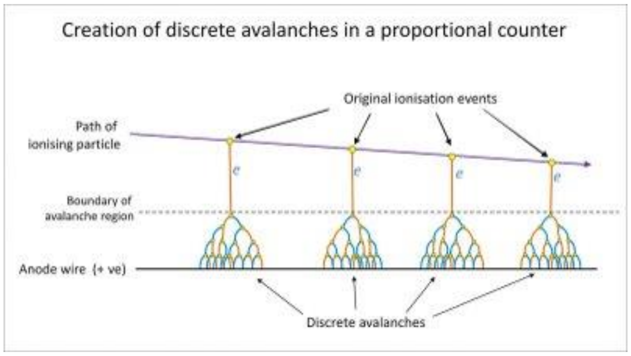

Figure 2. A diagram of Townsend avalanches being created in the wake of a particle path. Image from Wikipedia.

The total number of electrons in any avalanche that reach the anode is equal to the number of ionizing collisions plus one (the primary electron). This is because each gas molecule only gives up one electron per collision. This multiplication of freed electrons from ionization is known as gas gain and can be as high as a factor of 10^6 or 10^7;[8] this relates to the number of electrons that reach the anode and is what determines the strength of the induced current, which can range from 10^{-18}A to 10^{-5}A. Even at the high end of that range the current is very small, thus detection electronics will be needed to amplify the signal further.

Ionization voltages can be divided in three regions: Ion chamber region, proportional region, and the Geiger region. In the ion chamber region the electric field is not strong enough to trigger avalanches. Ions and freed electrons will move towards their respective cathode or anode, and they will not recombine. In the Geiger region the electric field is so strong that avalanches are so numerous and the entire gas volume around the anode is ionized. If this occurs, then all energy information is lost from the read out pulses. Beyond the Geiger region the gas is in continuous discharge as the breakdown voltage has been reached.[9]

For this project the proportional region is of most interest. This is the region of electric field strength between the ion chamber and Geiger regions, and is for our purposes "just right." In this region avalanches occur around the anode proportional to the number of original ionization events. This allows determination of the energy of the original ionizing particle by the size of the pulse created.

2.3 Design

The detector frame is 20.3cm (8.0in) square with a detection side length of 15.2cm (6.0in) square. This size is somewhat arbitrary, but it is the largest size that can comfortably fit in the print bed of the 3D printer. The frame is printed as a single piece from polylactic acid (PLA) which is a plant-based, biodegradable ecoplastic. The frame is 1.0cm wide and 2.0cm tall, therefore the distance between cathode plates is 2.0cm. This gives a total gas volume of

462 cubic cm, and detection area of 231 square cm. On two opposite sides of the frame we have designed a *bridge* consisting of a narrow wall making a lip over a large flat region. The bridge has printed onto it small grooves for the wires to sit. These grooves provide exact spacing and stability for the wires. The flat region will have glued to it a custom circuit board with copper contacts onto which the wires will be soldered. One side of the chamber holds the circuit board for input voltage, and the opposite side holds the output board. On the sides of the frame perpendicular to the wire bridge are two holes tapped for gas flow nozzles.

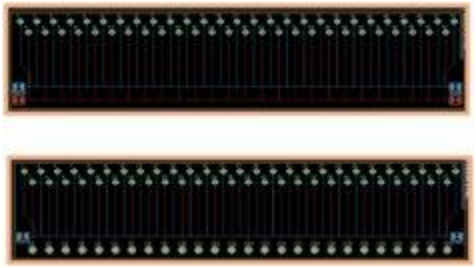

Figure 3. Schematics of the circuit boards designed in EagleCAD.

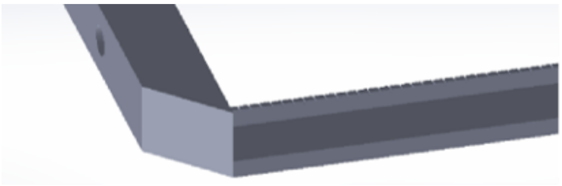

Figure 4. SolidWorks image of a section of frame. Note the grooves for wire placement, the flat region to hold the circuit board, and the hole for gas flow.

The wire array makes a plane exactly halfway between the two cathode plates. Wires are spaced 3mm apart, and the array alternates between *field-shaping* and *anode* wires. The anode wires are 25 micrometer thick gold-plated tungsten[10] and the field-shaping wires have been 100 micrometer thick copper in past prototypes[11], but our newest chambers are using the same gold-plated tungsten instead because it is stronger than copper. Copper is cheaper, but since the chambers are so small the gold wires can be used for the entire array without impacting the cost significantly. The field-shaping wires are grounded to the cathode plates and serve two primary functions: To shape the electric field as to converge all local electric field lines onto the anode wire, and to isolate the anode wires from each other. This eliminates cross-talk, gives better resolution, and stronger pulses.

3. Bench Testing: Fitness

Our wire chambers undergo three primary fitness tests before they can be deemed fit for operation: voltage, gas seal, and pulse transmission. If any of these tests fail, then there is a flaw in the construction of the chamber that must be addressed.

The high voltage test will send up to 2.5kV to the anode wires with the field shaping wires and cathode plates at ground. The purpose of the test is to make sure that the chamber can hold voltage with no current being drawn above about 100nA.[12] Detection of a particle depends on being able to read a current pulse from the event. If there is leakage current between the wires, then that pulse can be affected. Furthermore, the current will produce a magnetic field that can cause the field-shaping wires and anode wires to be attracted and result in a wire snapping. Each anode wire represents an open circuit, so no current will travel between them until a pulse event temporarily closes the circuit.

The first prototypes did not pass the voltage test. The circuit boards used for the wire connections was a simple copper clad perf-board that was not rated for high voltage. Several fixes were attempted, including sanding the copper off of the board between the wires as to increase the arcing gap, and creating custom wire harnesses to further insulate the connections between wires. Despite these efforts the original prototypes failed. A higher quality board was required.

The author used a CAD program called Eagle[13] to design custom circuit boards and sent the files to a manufacturer. Each board is two layers, top and bottom, with high dielectric strength material between the layers. Each wire has a dedicated solder pad with a copper trace running to the power rails on the input side, and on the output side each anode wire pad has a trace to a dedicated output node. The high dielectric strength combined with the two-layer design of the custom circuit boards is sufficient to pass the voltage test.

The gas seal test is required to ensure the chamber can hold the gas volume at atmospheric pressure. There is a very slow gas flow[14], so small leaks are acceptable as long as atmospheric pressure is maintained in the chamber. Presently the flow regulator is set to 50mL/min to slowly exchange the gas volume in the chamber. Initially the gas seal was made by simply gluing the cathode plates to the frame. This was not helpful for two reasons: gas still found ways to leak out of the joints, and once glued shut the chamber could not be opened again. To resolve this issue the frame was redesigned to accommodate an o-ring to form a better seal. The newest prototypes are being tested with the new sealing technique.

The pulse transmission test is to ensure that a signal can successfully travel from the input terminal to the output terminal without attenuation or distortion. This is achieved by using a pulse generator to send a variety of signals including sine waves, square waves, and pulses through the input and read out on an oscilloscope from the output. So far all prototype chambers that can hold voltage have passed this test.

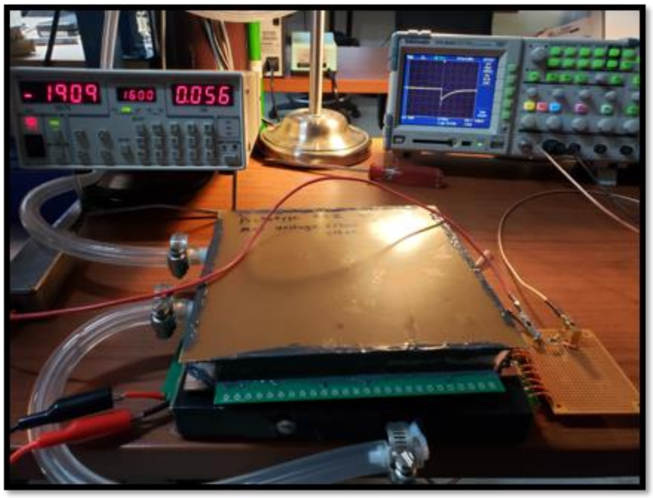

Figure 5. Bench testing set up. There are two chambers stacked, both with gas flow, however only the bottom chamber has voltage. Polarity is reversed in this set up.

3.1 Noise Reduction

The chamber itself has a resonant structure at certain electromagnetic frequencies, much like how a woodwind instrument, such as an oboe, has characteristic resonant structure at certain sound frequencies. The chamber was tested for its resonant structure by running a frequency sweep through a network analyzer. The frequency sweep ran from 300kHz to 300MHz, and was read out on a graph of dB attenuation vs frequency. Results showed that after about 30MHz resonant structure and dead zones begin to form, but up to that point the structure is very flat. This means that any pulse received below 30MHz will be unaffected by the resonant structure and will be transmitted accurately. However, any signals received above this threshold will become distorted or lost completely. The relationship between frequency and period, or in this context pulse width, is reciprocal. Thus, 30MHz corresponds to 30μs and it is expected that the pulse from muons be well within this upper limit on period.

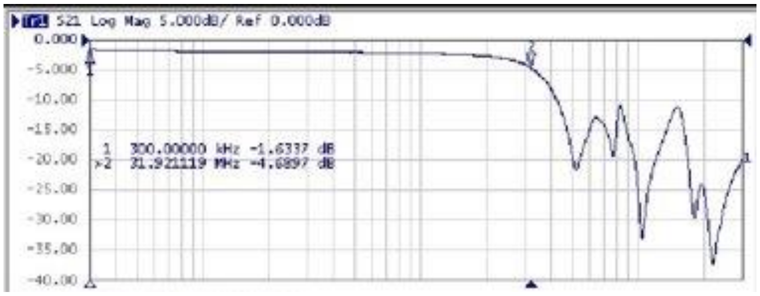

Figure 6. Spectrum analyzer read out of the resonant structure in the chamber. The axes represent dB vs frequency. The arrow marked ‘2’ is the half power point, where the resonant structure begins to form.

The other sources of noise are on the lower end of the frequency spectrum, such as the 60Hz power cycle that is created by any equipment connected to a wall outlet. The chamber acts as a radio antenna for any electromagnetic waves propagating through space, so lower frequency sources are susceptible to be picked up by the chamber contributing to noise and distortion of the signal. The easiest first defense to noise control is a band-pass filter. A band-pass filter is simply a high-pass filter in series with a low-pass filter, which cuts off all frequencies below and above a certain threshold allowing on the frequencies within the band to pass through. The author then constructed a band pass filter for to allow frequencies above 100kHz and below 30MHz. This effectively cut out the 60Hz power cycle which we observed being picked up by our chamber, any other very low frequency noise that could interfere, and the high frequency resonant structure that we also observed in the chamber.

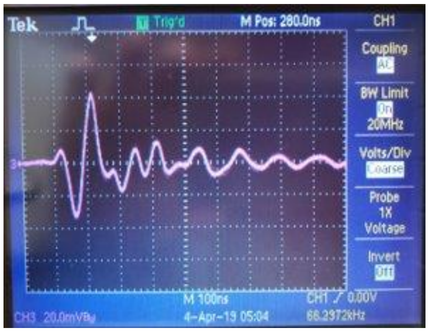

Figure 7. Oscilloscope read out of resonant structure noise in the chamber. This very stable waveform corresponds to Figure 6. They are Fourier transforms of each other.

This method of noise reduction is very broad however, and as signals from radiation are seen within our chamber other noise reduction methods will be employed to help clarify the signal, including narrowing the band-pass filter to contain only the frequency range required to observe the pulse.

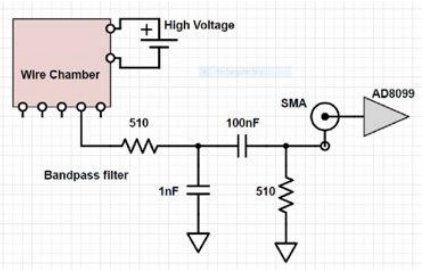

Figure 8. Schematic of the band-pass filter between the chamber and the SMA output.

4. Simulations

The author also performed simulations in the COMSOL Multiphysics[15] program of the electric field strength inside the chamber. The simulation was constructed for a single anode wire with a field-shaping wire on either side and a section of cathode plate above and below the wires. The geometry of the chamber and dimensions of the components were accurately reconstructed in the COMSOL environment, including the materials: copper cathode, copper field-shaping, and gold anode wires. In the simulation, 2kV was applied between the anode and cathode.

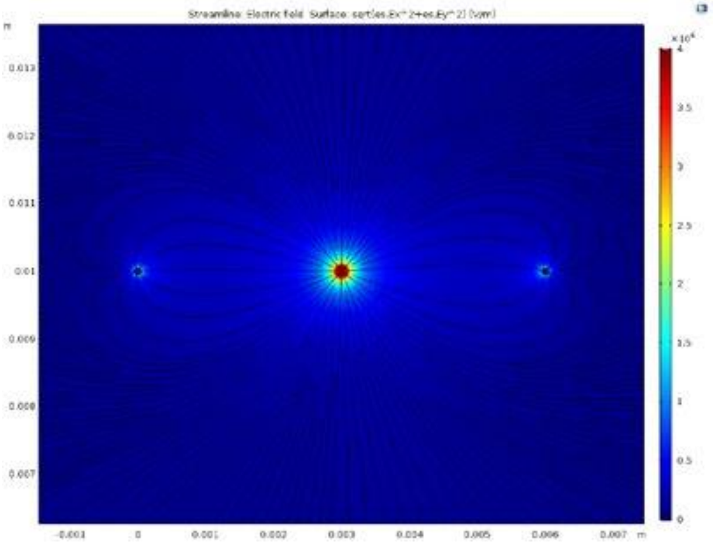

Figure 9. COMSOL simulation of three wires and cathode plates (not seen in image). The temperature map is electric field strength in V/m, and the electric field lines can be seen overlayed.

According to the simulations, the region immediately around the anode wires had extremely high electric field strength on the order of 3+ million volts per meter. This region is a cylindrical volume, the radial cross-section centered on the anode wire with a diameter of roughly a half of a millimeter. Beyond this region the electric field strength weakens drastically, as expected, in a circular gradient towards the field-shaping wire on either side.

The electric field lines are shown converging in increasing density toward the anode wires. This was as expected. The isolation of the anode wires is to provide better resolution, stronger signals, and eliminate crosstalk between anode wires. Freed electrons in the gas volume will be guided by the electric field to the anode wires and will be accelerated by the increasing field strength as they approach.

Figure 10. ComSol simulation of the electric field lines inside the entire chamber. The white regions are centered on the field shaping wires and the dark areas are where field lines converge on the anode wires. The isolation of anode wires is clear. Image courtesy of Dr. Kevin Stokes.

5. Conclusion

The region where the electric field strength is strong enough to initiate a Townsend avalanche is still to be determined. Initially it was believed that the field strength would need to exceed 3 million volts per meter. The size of the avalanche region depends on the strength of the electric field which is proportional to the magnitude of the applied voltage. The author believes that a lower applied voltage would still result in a sufficient avalanche region, thus providing a proper environment for the detection of beta particles and cosmic ray muons.

The present chamber design has been determined to be fit for particle detection, as the chambers now pass the three fitness tests described above. Small changes to the design of the chamber notwithstanding, the research group can say that the first milestone of producing chambers for muography has been reached and can now focus attention to identifying and shaping signals.

6. Acknowledgements

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