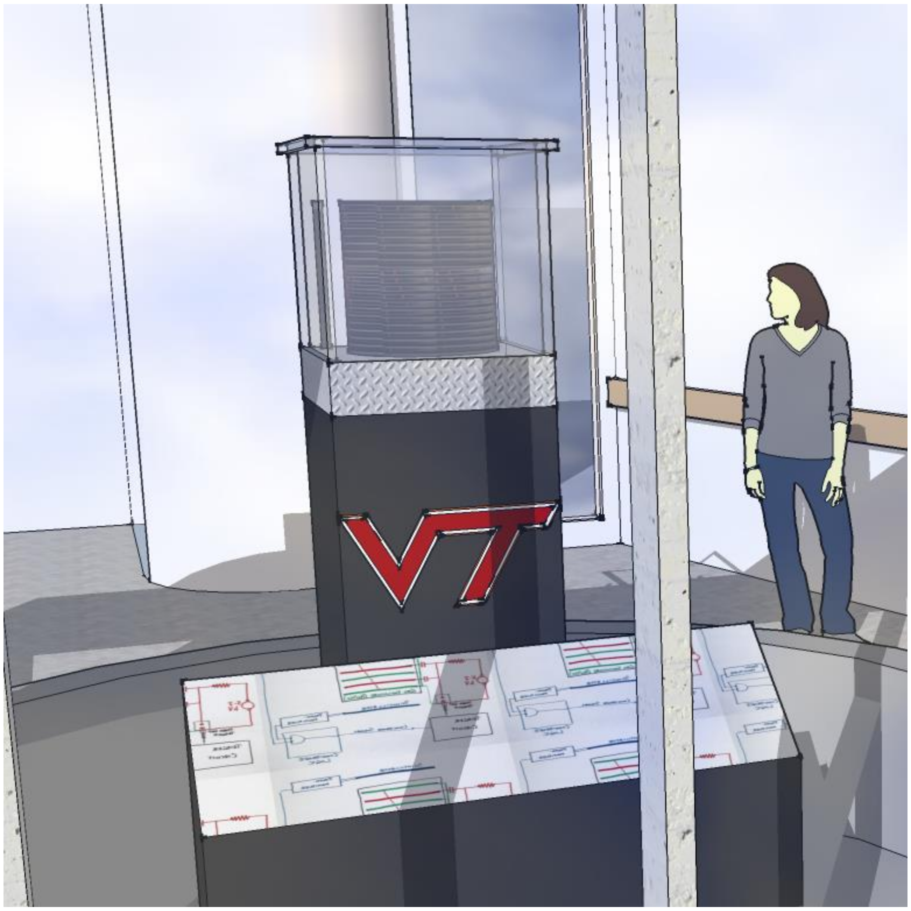
Conceptual Design Report
For the
Virginia Tech Senior Lab Spark Chamber



Conceptual Design Report
For the
Senior Lab Spark Chamber
At the
Virginia Polytechnic and State University

Prepared by:

Nicholas Merrill

Advisor:

Johnathan Link

Contributors

Below is a roster of the spark chamber design and their main contributions to the project and this report as part of their the Spring 2012 PHYS 4316 senior lab class

Jonathan Link	**Faculty Advisor**
Nicholas Merrill	**Project Coordinator & Physical Design**
Sam Rosencrantz	**Spark Physics**
Andy Lassiter	**Spark Physics**
Emily Acken	**Safety**
Derric Featherstone	**High Voltage & Trigger Circuit**
Fahad Pasha	**High Voltage & Trigger Circuit**
Peter Raum	**Coincidence Logic**
Michael Fagan	**Coincidence Logic**
Chris Fieldman	**Gas Physics and Implementation**
David Finnbogason	**Gas Physics Implementation**

1 EXECUTIVE SUMMARY OF THE PROJECT 5

2 SCIENTIFIC MOTIVATIONS 6

2.1 Introduction 6

2.2 Muon Physics 6

2.3 Detections physics 7

2.4 Spark Physics 8

3 DESIGN CONCEPTS 10

3.1 Examples 10

3.2 Physical Design 11
  3.2.1 Electrode 12
  3.2.2 Support Structure 13
  3.2.3 Chamber Design 14
  3.2.4 Gas and Electronic Housing 14

4 ELECTRICAL COMPONENTS 15

4.1 Coincidence Detection 16

4.2 Signal Amplification and High Voltage Trigger. 17
  4.2.1 BJTs(Biploar Junction Transistors) 18
  4.2.2 IGBT (Insulated Gate Bipolar Transistor) 19
  4.2.3 PSpice Model 19
  4.2.3.1 PSpice Analysis 20
  4.2.4 High Voltage Pulse Transformer 21
  4.2.5 Spark Gap 21

5 GAS SYSTEM 22

5.1 Characterisitcs 22
  5.1.1 Quenching Agents 23

5.2 Gas System Design Options 23
  5.2.1 Option 1 24
  5.2.2 Option 2 24
  5.2.3 Option 3 25
  5.2.4 Option 4 26

6 SAFETY 27

6.1 Gas Safety 27

6.2 Spark Safety 28

6.3 Maintenance 28

7 PROJECT SUMMARY 29

7.1 Summary of Systems 29

7.2 Summary of Costs 30

1 Executive Summary of the Project

This document describes the conceptual design of a spark chamber for muon detection and display. This spark chamber when completed will be displayed in the windowed area of Hahn Hall North room 103, the main lab room. Its purposes are to serve as a visual display and muon educational tool for the general public. This document will serve several purposes. First, it will describe the physics of muon detection and spark formation. Secondly, while allowing room for revision, specific design choices will be motivated and the pros and cons of decisions yet to be made will be made. Lastly, it outlines the steps to be taken to complete the design and construction of an operation spark chamber.

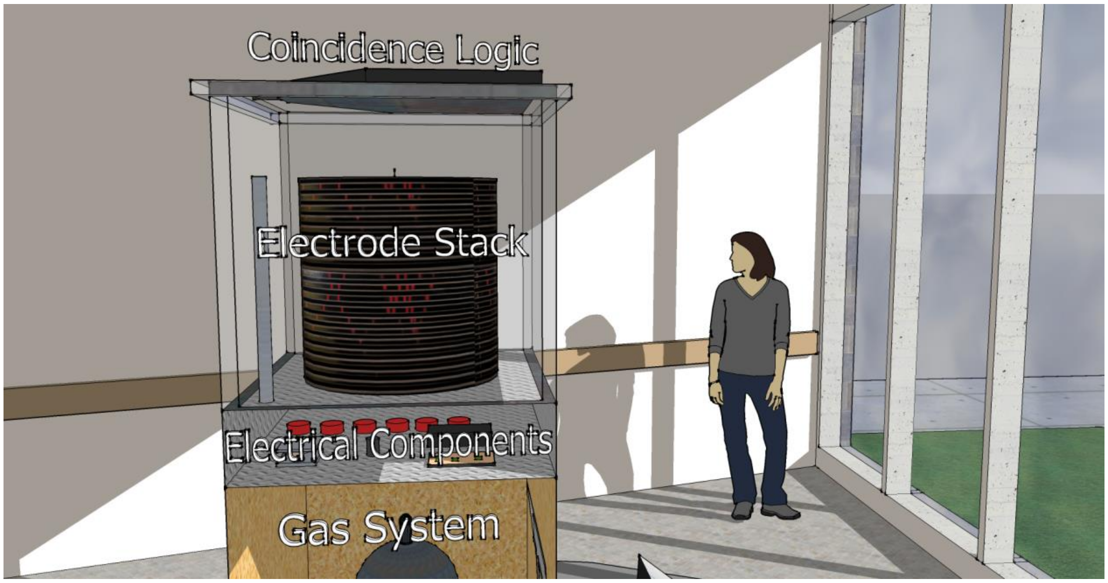


Fig 1. Visual Breakdown of the Spark Chamber Systems

Fig. 1 above provides a visual outline of the main components of a spark chamber design. The Coincidence Logic groups the tasks of detection by scintillation and photomultiplication and detecting a coincidence of two events from a single muon passing through the chamber. The electrode design includes the physical design of the plates, their support, structure, and their connections to the triggering electrical components. The Electrical Components include the multiple step amplification of the coincidence signal and the triggering of a capacitor bank discharge to force spark formation in the wake of a muon path. The gas system includes the physical design of an airtight transparent display chamber and implementation of a suitable gas.

2 Scientific Motivations

2.1 Introduction

A spark chamber detector is most basically is a stack of alternating high voltage and grounded aluminum plates, meant to discharge along the ionized track left in the wake of a charged cosmic particle, such as a muon, passing through the detector.

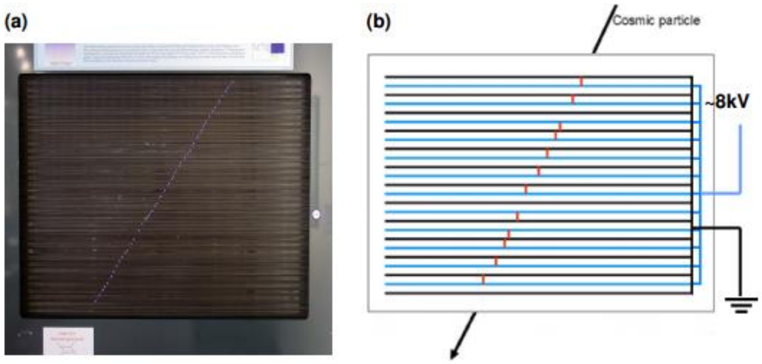


Fig 2. (a) Photograph of sparking in Vienna's Technisches Museum's spark chamber alongside a simple cartoon (b) Illustration of the track formation process

The discharge of the stacked plates along the ionized trail illuminates the path a cosmic muon followed through the detector. There are several necessary elements of an operating spark chamber. Most crucially is creating a sequence of operations to trigger a plate stack discharge precisely in the wake of muon. The chamber must also be isolated in an environment of a noble gas such as Helium, Neon, or Argon, which is favorable for spark formation limited to the path of the muon. Though the experimental uses of a spark detector are extinct, the demonstration and educational purposes of such a detector are significant and desirable. The Virginia Tech physics department is investigating into the possible construction of spark chamber detector by an undergraduate class, PHYS 4316, a second semester, senior lab.

2.2 Muon Physics

The top of earth's atmosphere is bombarded by a flux of high energy charged particles, approximately 98% being protons, produced in the other parts of the universe. The cosmic rays collide with the nuclei of air molecules and produce a shower of particles that include protons neutrons, charged and neutral pions, kaons, photons, electrons, and positrons. These secondary particles then undergo weak and electromagnetic interactions, decaying into additional particles in a chain.

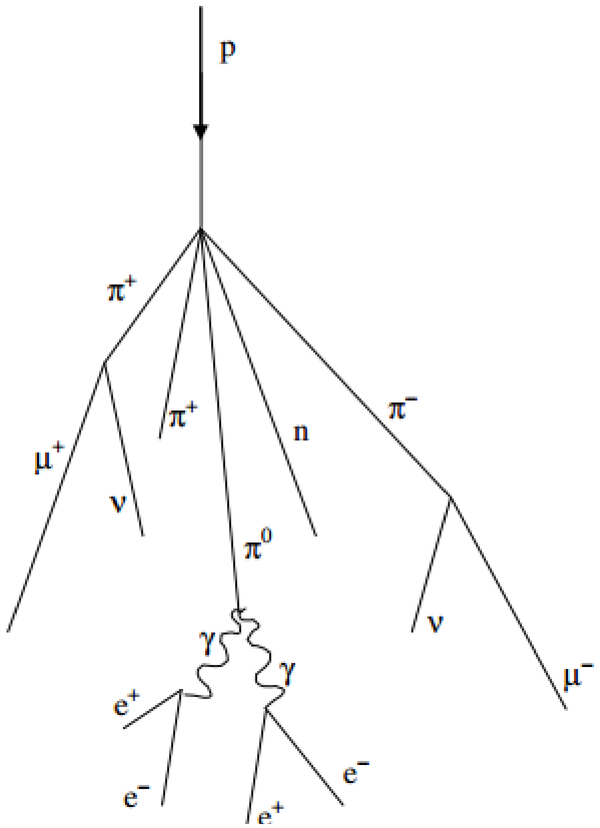


Fig 3. Cascade From a cosmic ray proton

Of particular interest is the fate of charged pions. Some will decay spontaneously via the weak force into a charged muon and neutrino or antineutrino.

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The muon (μ) is a much heavier unstable cousin of the electron. Like the electron it does not interact via the strong nuclear force, and is affected only through the electromagnetic and weak forces. The cosmic muon travels long distances before eventually decaying into a electron and neutrino/antineutrino pair. Atmospheric interactions and natural decays, only roughly 110 atmospheric muons per square meter per second arrive at ground level with a mean kinetic energy around 4 GeV, providing an ample natural source for the spark chamber to detect [1].

2.3 Detections physics

The role of a spark chamber's electronics begins ideally, when an atmospheric muon hits the plastic scintillator. The scintillator is made out of florescent plastic that is excited by the passage of an ionizing particle, such as a muon. Excited electrons in the florescent plastic have a primary decay back to the ground state that emits a photon. The photons can be be detected by photomultiplier tubes (PMT) or avalanche photodiodes. Early experiments in detection calibration were performed with photomultiplier tube, so they are the primary source of discussion in this paper. The scintillator is protected by light blocking material to prevent interference. A PMT first detects an incoming scintillation photon through a photosensitive surface called a photocathode, which releases electrons that are multiplied by ectrodes known as metal channel dyodes. At the end of a several step amplification is an electron collecting anode that drives an electrical current in the form of an analog pulse [2]. Not every muon will provide a detectable photon, and not every photon will drive a PMT signal, but the muon rate is sufficient enough to account for these short comings.

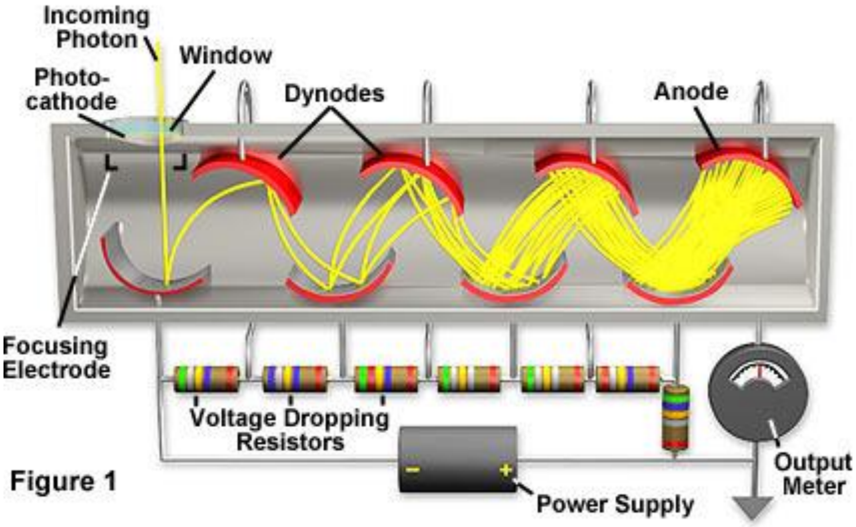


Fig. 4 Photomultiplier Tube

2.4 Spark Physics

An e atmospheric muon passing through the detector chamber, it releases some of its energy through electromagnetic interactions in the detector gas. Some of the valence electrons in the gas will be ionized along the path of the muon, creating a wake of ions and free electrons. The charged particles left by the muon act as the seed elements for spark formation.

Once the particle has passed through the detector a series of electronics creates a large voltage difference across the electrodes in the chamber. The electric field created by the potential difference accelerates the seed electrons away from their positive ion pairs.

These accelerated electrons gain enough energy in the electric field to liberate more electrons and ions, in a chain reaction, forming a local avalanche of electrons at the head of the trail and positive ions at the tail. As the number of electrons in the head increases, the avalanche begins to slow due to the attraction of the positive ions. At a critical amount, the number of separated ions and electrons is enough to create a local electric field that overcomes the electrical field driven by the plates. At this point, ions and electrons recombine within the local electric field caused by the avalanche. The recombining electrons release photons isotropically away from the avalanche.

These seeds will form separately but align head to tail as the streamer forms. The dipole field from the original avalanche inhibits avalanches to the left or right but encourages their formation in a streamer between the two electrodes. Once this streamer is fully formed a conducting channel of plasma is present that allows charge to flow through it from one electrode to the other and then to ground. As electrons recombine with their atoms photons are emitted isotropically from the avalanche.

The emitted photons ionize surrounding molecules in the vicinity of the original avalanche. The dipole field from the original avalanche inhibits avalanches parallel to the E field between the plates, but encourages their formation between the two electrodes. New avalanches rapidly form until the old and new avalanches merge, forming a streamer. The extremities of the streamer grow, connecting the plates by a low resistance conducting plasma of electrons and positive ions, which extends in a parallel direction to the electric field lines. A spark subsequently passes between the two plates [4].

As electrons recombine with their atoms photons are emitted with energies indicative of the energy shell transitions of the ionized gas atoms. The wavelengths of the photons released by these transitions determine the spark color.

The spark formation is strongly related to the choice of gas by the energy requirements to liberate valence electrons. The average number of ions per centimeter formed in a path travelled by a cosmic ray is listed as 8 ions per centimeter for Helium, 43 ions per centimeter in neon, and 94 ions per centimeter in argon [4].

3 Design Concepts

The final design of the spark chamber should fulfill several major requirements.

- The spark chamber must aesthetically pleasing in its proposed placement in Hahn North
- It must be visually accessible from both outside and from within the laboratory
- It should not pose any danger to the public or electronic equipment
- It should be reasonably maintainable

3.1 Examples

Research into other spark chambers included other university projects and papers talking about the

typical and general specifications that a spark chamber would need in order to work. By far the two most typical designs are a sandwich model and stack model.

The stack model is the most simplistic. It simply creates a tower of electrodes supported by a structure that ensures even spacing and usually provides a single frontal viewing angle. The stack sits in an chamber filled by a single gas system. The stack design can potentially lead to sagging which could cause unwanted edge discharge. Typically this occurs at the corners of the plates, which are rounded to compensate. The University of Cambridge Mark III design provides a sturdy straight forward example [5].

The University of Birmingham built a sandwich design. In this type thin electrode sheets are glued on two sides of a highly polished Perspex frame. These sandwiches have individual gas connections to provide a constant flow of gas to account for the larger number of seals and potential leaks. An advantage of this design is the removal of edge discharges and sagging. The thick windows of this design do pose a problem for optical clarity, especially at non-optimal viewing angles, where the refraction through a thick piece of Perspex could be severe [6].

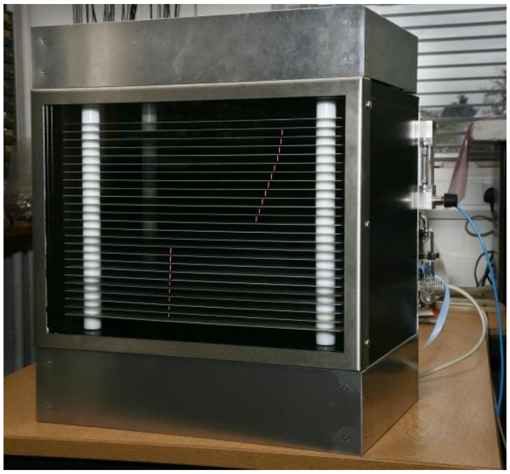


Fig. 5 University of Cambridge Stack Design

Fig 6. University of Birmingham sandwich design

There is a third more novel design incorporates a bell Jar. The University of Buffalo has a stacked design in a glass bell jar. This would work well for the chamber being visually accessible from multiple angles, but provides no easy place to store the Scintillation and detection equipment, forcing an awkward, unfavorable aesthetic. The yet untested University of Manchester design corrects this by building the detection equipment into the stack inside of the bell jar, but provides two major drawbacks [6].

The lack outer placement of the supporting structure may lead to an uneven electrical gradient in the middle of the stack. Following such a novel untested design is unadvisable. For instance, the gas system, if it includes helium could quickly destroy the scintillation equipment if mounted inside the chamber such as in the Manchester Design. A bell jar or cylindrical window design also carries a significant price tag.

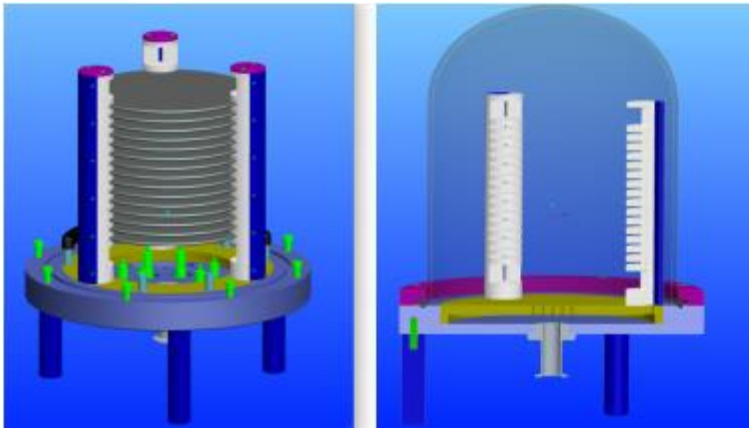


Fig 7. University of Manchester Bell Jar Design

Plate sizes varied between individual designs. There seems to be a limit on sheet thinness, which is more likely to dip from instability. Cambridge commented on random sparking from a plate thickness of 6mm, while the IPP Outreach group reported success with 1mm thickness [5, 8]. Thinner plate thicknesses also make machining more difficult and expensive, but the material cost is obviously less. Visibility suffers at larger plate thicknesses, so there presents a tradeoff in either direction. Gap distance and gas composition also play large rules, primarily in the required high voltage supply. Most separations centered around 1cm. Argon, Neon, more rarely Helium, or some mixture of the three served as the gas supplies. The high voltages across the plates varied from 6kV with one Helium design up to 10kV [9, 10] .

3.2 Physical Design

The current design of the spark chamber considers the examples of other Universities. It combines the visibility of a circular bell jar design, with the sturdiness and simplicity of the central stack design, while minimizing the problem of edge discharge.

3.2.1 Electrode

The circular electrode design was created to balance visibility while considering the possibility of unwanted electrical discharge caused by dipping. The design incorporates a three tower support structure. The diameter of the plates is designed to maximize the use of an 18” typically sized sheet that they are likely to be machined from.

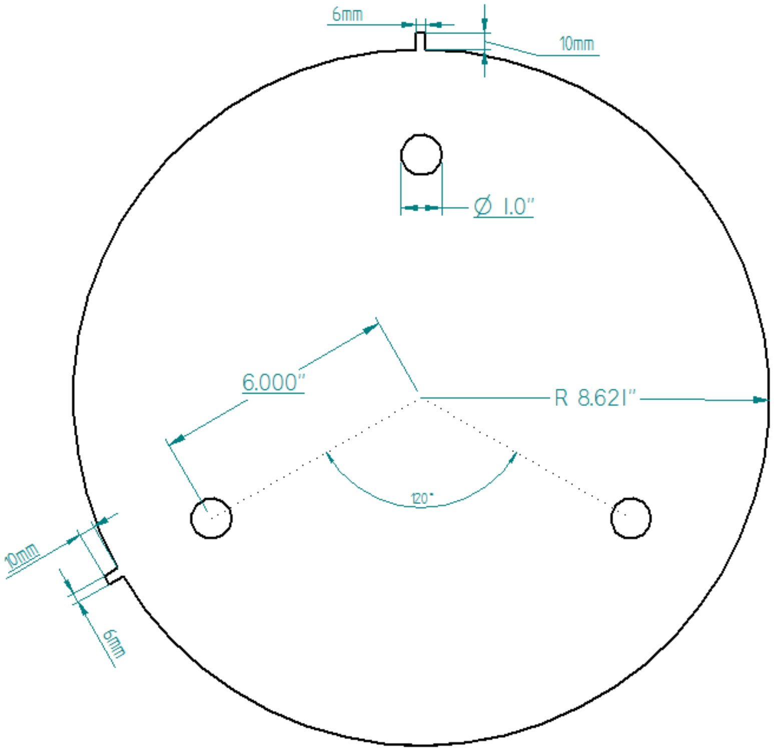


Fig. 8 Electrode Plate Design

A stack of 41 electrodes can be machined out 0.1” (0.254cm) sheets of an unspecified aluminum alloy. The support structure will run through the three cut out holes located at the centroid of the one-third circle pieces.

$$\bar{y} = 0.705R$$

The tabs located at the two sides of the plate will serve as electrical connections to the ground and high voltage capacitor bank. Though only the HV plates require both tabs, the belief is that machining them from a single design is the economical option. The tabs are built into the electrode, because the uniformity across the electrode is so essential to prevent unwanted discharge. Unfortunately this design creates a level of intricacy for machining the plates. The additional complication increases the cost of the machining, yet a better solution has yet to be found.

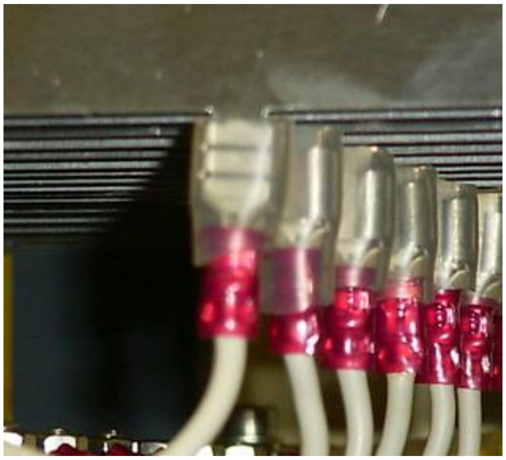


Fig. 9 Electrode connection to HV [8]

3.2.2 Support Structure

Following the examples of the IPP Outreach Group and the Cambridge Mark III a tower support structure was adopted. The towers run the length of the stack through the centroids of the one-third circular sections. The towers are to be built from 1” diameter 23” longs Delrin rods. Delrin (acetal homopolymer) is a rigid, machinable, insulating plastic, which is marginally more expensive than a comparable acetal copolymer [11].

The spacing of the electrodes is provided by 1cm thick Delrin Spacers with an inner diameter of 1” to be designed to fit around the rods, and an outer diameter of 1.5” to provide a lip for the electrodes to rest. The spacers are to be machined from a single tube. The uniformity of these spacers is vital, so the tolerances for this machining will need to be small. The 8cm long bottom spacer is larger to provide an insulating cushion between the electrode stack and the base of the chamber. The top and bottom inch of the support rods are threaded so custom Delrin nuts can screw down the stack providing extra support.

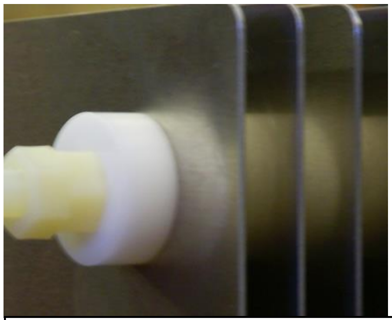


Fig. 10 Top nut and spacer [8]

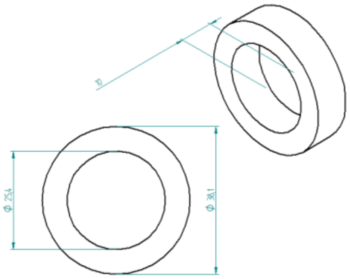


Fig. 11 Spacer design

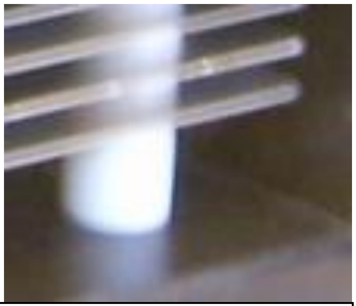


Fig.12 Large Bottom Spacer [8]

3.2.3 Chamber Design

An open visible housing contains the gas. Like the bell Jar a cylindrical housing is possible, but far more expensive. Instead, A square on can be constructed. The goal is it to to have as many pieces as possible made from or compromise of a standard 24" x 24"sheet of Lexan for economy. Lexan is a polycarbonate that is much more resistant to impact as well as being more electrically resistant than Plexiglas. Plexiglass however, is a cheaper, suitable substitution. Multiple pieces can be chemically cemented together to make 5 out of the 6 sides of an airtight chamber. The bottom side can be constructed from a different material, likely PVC, and will have a groove as well as a slot for a perimeter of O-ring cord stock to finish off the seal. The Lexan, will be screwed down across the lip of the bottom side to provide an air-tight, but removable, gas chamber. Figs. 13 and 14 outline this basic design this design.

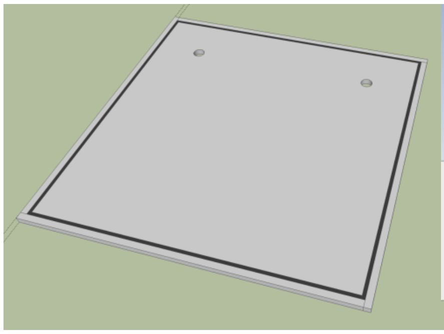


Fig. 13 PVC Chamber Base

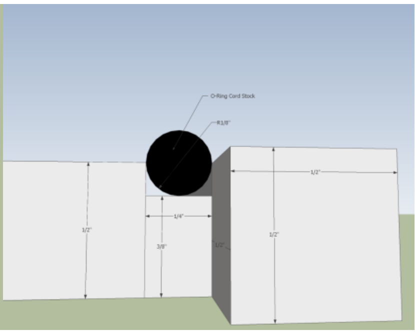


Fig. 14 Base Cutaway

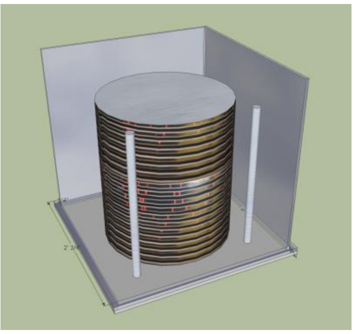


Fig.15 Chamber Cutaway

The holes present in the base will serve as the electronic connection between the electrodes inside of the chamber and the electronic components below it. Threaded aluminum rods with ½" diameters will pass through the holes fitted with self-sealing washers and nuts on both sides to maintain the air-tight seal. This design should be effective in minimizing the number of leaks. The decision to string the capacitors that will hold the high voltage charge individually on the inside of the chamber or to build a single capacitor bank outside the chamber is yet to be made.

Having all four sides may pose a problem for spark visibility. Most designs unlike ours have a dark back wall to make the spark more pronounced [8, 5].

The gas connections are not shown in these diagrams, but there placement and design need to be settled upon before progressing with the chamber design.

3.2.4 Gas and Electronic Housing

Specific designs for the electronic and gas system housing to be placed below the chamber have yet to be created. It is recommended though to construct the electrical housing from cheap sheet metal, but making it more than capable of supporting the chamber weight. The gas system housing in the main pedestal structure can easily be made from cheap wood and screws, again, making sure to reinforce to handle the appropriate weight.

4 Electrical Components

The electronic components in the spark chamber detector act as an overall system to trigger a High Voltage discharge in the wake of a muon passing through the electrode stack.

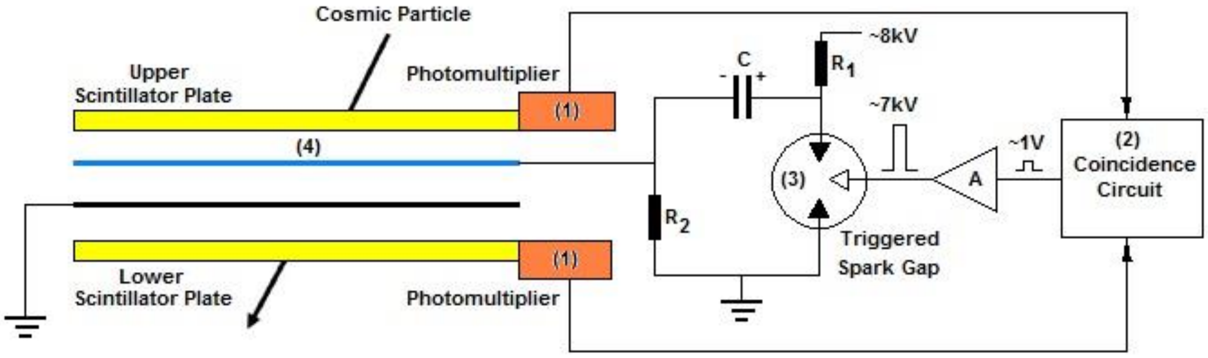


Fig. 16 Simplified Circuit

As Fig 16 illustrates, at point (1) Scintillator plates detect a particle passing through the chamber signaling the coincidence unit at point (2). Once the signal pulse from the coincidence unit is isolated it is amplified, triggering a discharge across the spark gap at point (3). This short across the gap discharges the capacitor C and drives a high voltage step onto the chamber plates at point(4). As all the plates in the chamber get grounded, capacitor C recharges through choking resistors R1 and R2.

To summarize the operation of the circuit, a -1V pulse is sent to the BJT, switching it on to its forward active(on) state. A larger, -10V, pulse is then sent to the IGBT, turning the IGBT on to allow an even large pulse,-130V, to be sent to the transformer. This pulse is amplified further to discharge the spark gap which ultimately sends a large high voltage, -8kV pulse to the plates. The BJT and IGBT should operate without any issues since the voltages they are handling are well within their operating regions. Even the occurrence of multiple muons simultaneously passing through the detector should have no damaging effect on the circuit, as this simply would leave the IGBT's and BJT's on longer than they normally would be. This conceptual design should prove to be successful, considering results of using similar design in the past.

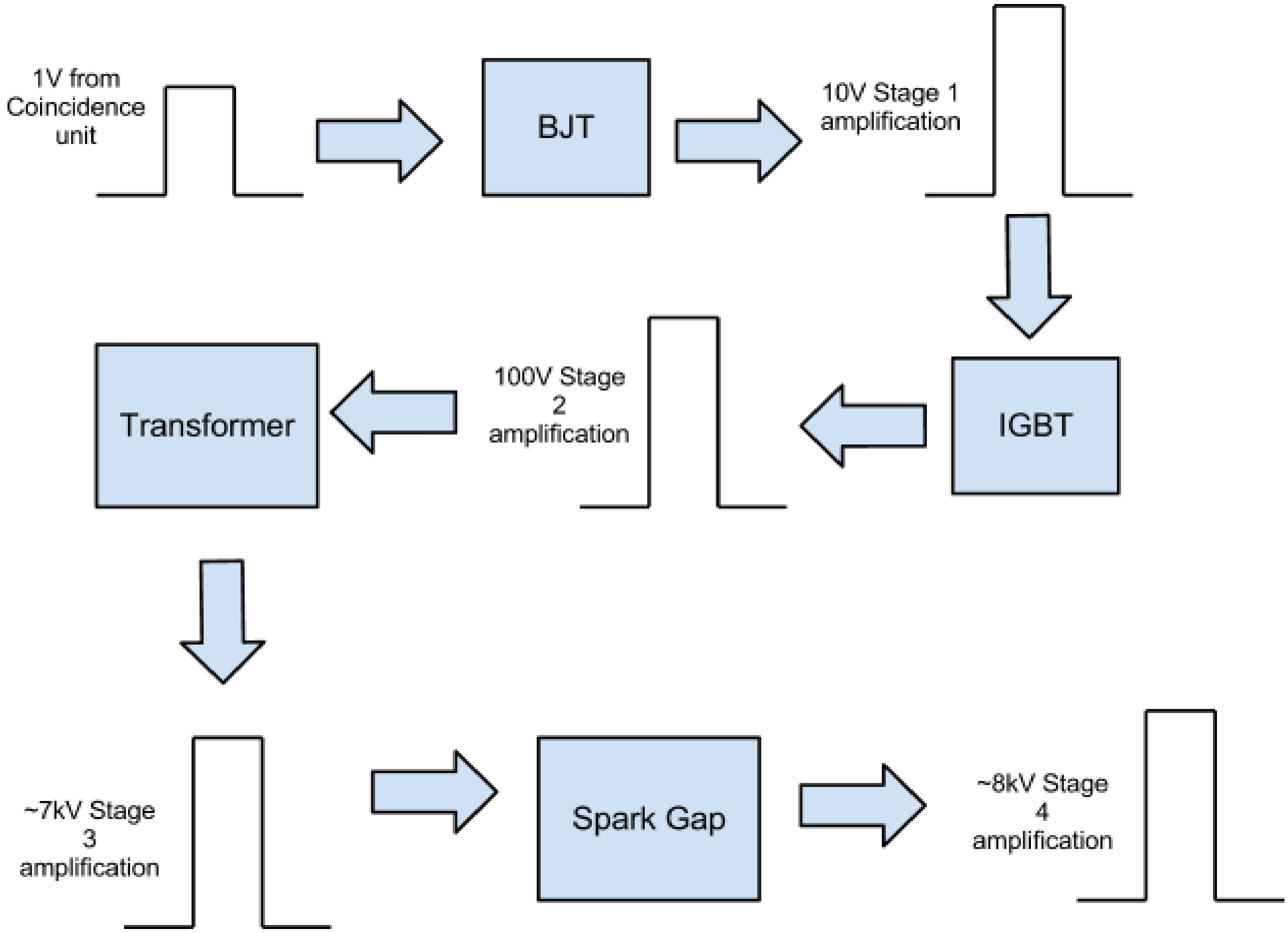


Fig. 17 Summary of Circuit Design

4.1 Coincidence Detection

Experiments were conducted with existing scintillator paddles, but it is possible to construct new ones. Berkely Lab outlines an example construction [13].

The role of a spark chamber's electronics begins, ideally, when a cosmic ray muon hits the plastic scintillator, causing the material to fluoresce. The emitted light from the scintillator goes to the adjacent photomultiplier tube. The photons, in principle a PMT can be triggered by only one photon, dislodge electrons in the PMT from a charged dynode, and those electrons free more electrons from a series of dynodes, until the last electrons strike an anode and deliver produce an electric current in the form of an analog pulse. The overall job of the digital electronics is to take these analog pulses and determine whether or not they are energetic enough to be a real muon and whether they occur in both PMTs within a small enough time interval to correspond to a real muon going through both scintillators.

The first of those tasks is performed by a discriminator, which in the proposed circuit design, is handled by a simple comparator. The comparator takes as input the analog pulse coming out of the PMT, as well as a threshold voltage. If the pulse coming in the input is a higher voltage than the threshold, the comparator will output a square pulse of some supplied high voltage for as long as the input is over threshold; otherwise, it will output near-zero voltage. Addition of a variable resistor allows for easy tuning of the threshold. Exact tuning of the threshold voltage is determined by the characteristics of the photomultiplier tube being used, and is discussed in detail in the other section of this report. The length of the output pulse is related to the energy of the incoming muon. A more energetic muon results in a larger analog pulse which will be over the threshold voltage for a longer period of time and cause the comparator to output a longer digital pulse.

The pulse travels from the discriminator to the last component our group handled: the coincidence unit, which is an AND gate in our design. The coincidence unit takes the digital pulses from the discriminators and outputs a pulse of a certain voltage if and only if it receives high voltage pulses from both discriminators at the same time. This filters out the vast majority of pulses which are caused by a muon going through only scintillator at a large angle off of vertical, as well as pulses caused by noise, although most noise should be filtered out by the discriminator. This output pulse from the AND gate goes to the high voltage/trigger circuitry and causes the spark chamber to “fire.”

The tuning of the PMT threshold to filter out the vast majority of noise as well as the necessity for two events to occur in coincidence for the chamber to activate means that the chance for noise causing the spark chamber to fire without a real muon traveling through it is quite low, however several potential issues came up during design. One concern is whether the pulse widths and timings will be correct enough that pulses will overlap when they reach the coincidence unit as expected. By a rough estimate it was determined that the electronics should work as expected without the need for any additional components, such as a delay. Because the threshold of the PMT is being tuned to between the noise and muon range, even most low energy muon pulses should be above threshold for a significant time interval. As long as cable lengths are roughly equal for each discriminator unit, the difference in time between when the muon hits the top and bottom scintillators should be only a few nanoseconds owing to the speed at which muons travel. Another important issue is exposure of the PMTs to helium. Helium can permeate a photomultiplier tube, increasing noise and eventually rendering it useless. Even exposure to the helium present in air can ruin a PMT over time, so if some gas mixture including helium is used in the spark chamber, care must be taken to minimize the PMTs exposure to it, or the tube’s operational lifetime may be severely decreased.

4.2 Signal Amplification and High Voltage Trigger.

The role of the triggering circuit is to specifically prevent a continuous discharge between the chamber plates. The trigger circuit needs to apply a high voltage, typically 8kV only immediately after a particle has travelled through the chamber, having been detected by the scintillators and receiving an input signal from the coincidence unit.

From the coincidence unit the trigger circuit expects short -1V pulses as indicators that a muon has passed through the detector. The ionized path breaks down rapidly, on the order of 500ns. Therefore, a high voltage pulse must be sent to the plates within that time to ensure consistent sparking of the chamber. To carry out this task, we’ve designed a triggering circuit to send an amplified input signal to a spark gap, which then shorts a high voltage power supply to ground. The high voltage power supply is also electrically connected to alternating plates, the result is a large step in voltage measured across the plates.

The trigger circuit is designed to amplify the input signal from the coincidence unit in a cascade like fashion. We decided to replicate the trigger circuit built for the spark chamber in Cambridge, which proved to be effective and relatively cheap to produce [12]. In order to fully understand the circuit the operation of several circuit elements need to be understood.

4.2.1 BJTs(Biploar Junction Transistors)

BJTs are a three terminal electronic device used in amplifying and switching functions. They're made of doped semiconducting materials and come in two structures; NPN and PNP. In the PNP type which is used in our trigger circuit, we have n-doped material sandwiched between two p-doped materials.

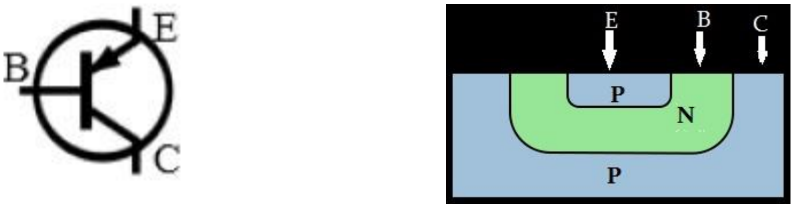


Fig. 18 Symbolic Representation of PNP BJT

Each BJT has three pins; the base, emitter and collector. The base pin is electrically connected to the n-doped material, while the other two pins access the p-type materials. The voltage at the base controls the current flow between the emitter and collector. The ratios of voltages between the base, emitter and collector offer a variety of regions of operation for the BJT.

Here we consider two possible states for the BJT; forward active and cutoff. Parameters found below:

$V(B) > V(E)$ and $V(B) > V(C)$; Cutoff(off) – no current flowing from Emitter to collector.

$V(C) < V(B) < V(E)$; Forward Active(on) – Current flows from emitter to collector

proportional to current flow from base to collector by an amplification factor β.

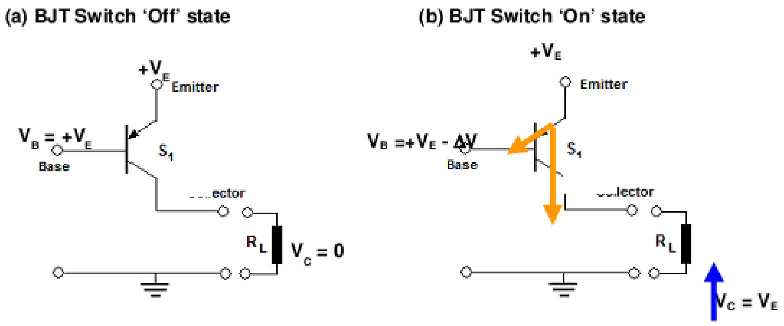


Fig 19. BJT Switching

4.2.2 IGBT (Insulated Gate Bipolar Transistor)

The IGBT is another three terminal switching device. Using a bipolar transistor as input control and a field-effect transistor (FET) as the switching mechanism, the IGBT can handle high currents and high voltages while maintaining fast switching capabilities. Similar to the base of the BJT, the gate voltage controls the current flow from the collector to the emitter. The gate must reach some threshold voltage in order to create a channel for current to flow between the collector and emitter.

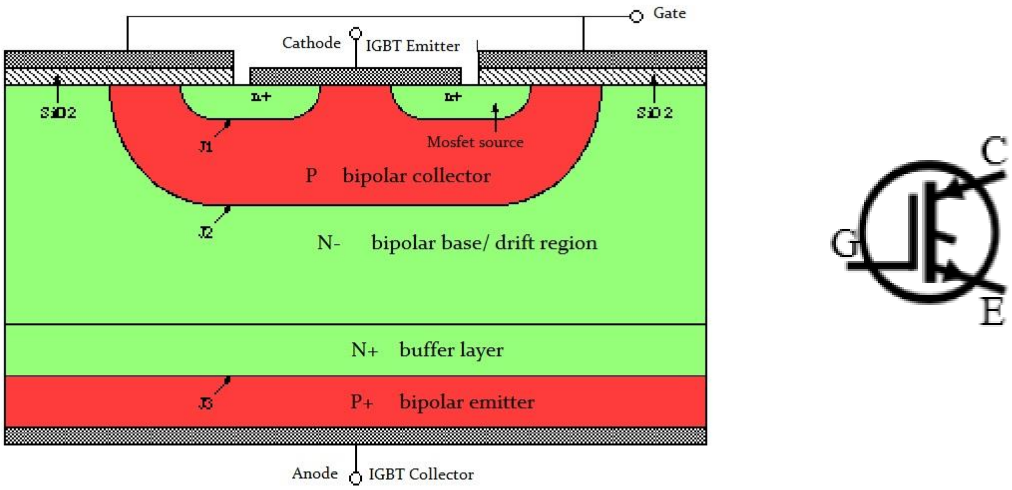


Fig. 20 Symbolic Representation of the IGBT:

4.2.3 PSpice Model

The software package used for simulating the electronics portion of the trigger unit was Cadence ORCAD PSpice 9.1. The license for the software was obtained through the Bradley department of Electrical and Computer Engineering. The student version of the software does not have the necessary part directories or internal architecture to support the operations of the IGBT in the circuit.

Prior to any fabrication it is often necessary to first simulate a circuit. By having the flexibility to change parts (i.e. Resistor/Capacitor values) we can develop a proper understanding of how a circuit works and what its limitations are. Since PSpice allows us to simulate circuits in several different modes, we limited ourselves to a transient time domain analysis, setting the run time to 3000ns.

With some minor changes, the design itself is heavily based on the circuit used in Cambridge [12]. However, due to constraints on access to what parts we had access to the BJT and IGBT parts were picked arbitrarily and then edited in PSpice to fit the needs of our project.

To simulate the input signal from the coincidence unit we placed a pulse generator with parameters that can be varied in Pulse Width (PW), Rise time (TR), Fall Time (TF), and Period (PER).

Discussions are ongoing with Dr. Meehan in the ECE department to determine the proper biasing modes for the IGBT and BJT to achieve the desired output.

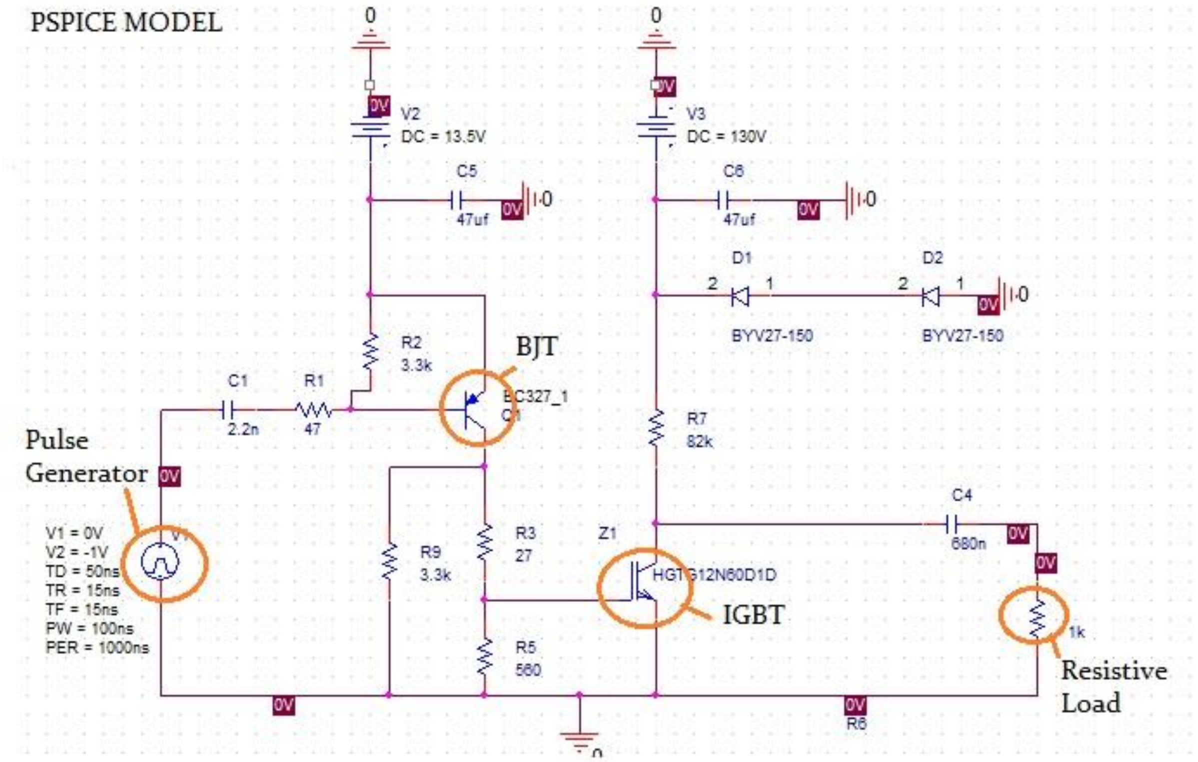


Fig 21. PSPICE Model

From the model it is seen how the BJT and IGBT fit into the trigger circuit. A -1V pulse is sent to the BJT. The signal is amplified by the BJT, and the pulse is further amplified by the IGBT. The pulse generator was used to mimic expected inputs from the coincidence unit, and we probed the voltage across and current through the resistive load to see what signals we might expect going into the transformer.

4.2.3.1 PSpice Analysis

In this circuit C1 and C4 function as high pass filters. C5, C6, D1 and D2 operate as surge protectors. R1 limits the current through the base, and R2 is placed to ensure that the BJT does not draw any current until the appropriate pulse is received. R9 together with R3 also form a voltage divider which controls most of the voltage going into R3. R3 and R5 form yet another voltage divider, controlling the amount of voltage that reaches the gate of the IGBT.

The BJT model had a gain, or β, of 300. The threshold voltage for the IGBT model was 4.5V. Ideally we want the voltage at the IGBT gate to sit just below the threshold voltage, so when a pulse comes through the IGBT readily draws current from collector to emitter. Considering R3 and R5, we have that the voltage at the gate is given by:

$$V(IGBT\ gate) = V(BJT\ Collector)^{*}\ R5/(R3+R5)$$

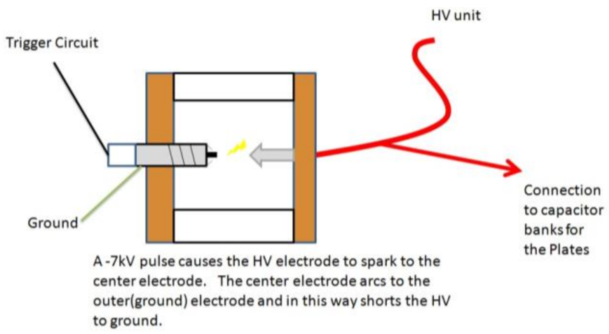
The PSpice models for the BJT and IGBT aren't exact copies of the chips we ordered, so adjustments will need to be made for the real components when placing them on a circuit board. In theory we would mainly need to adjust R2, R3 and R5 to compensate for variations in the BJT and IGBT.

4.2.4 High Voltage Pulse Transformer

The triggering circuit is designed to spark the spark gap, which will then short the 8kV high voltage unit to ground. However, the BJT and IGBT alone will not provide enough amplification to break down the spark gap. Therefore, a transformer is used to convert the incoming -180V pulse to a -7kV spike.

4.2.5 Spark Gap

The spark gap allows fast switching of high voltages. Ideally one would use a sequence of spark gaps in place of the BJT and IGBT to trigger the high voltage. However, spark gaps tend to be costly and need high maintenance, so our circuit will only use one spark gap in order to switch the high voltage power supply. We decided to build our own using a car spark plug to cut costs. The spark gap is housed in metal with nylon rods used to maintain a constant spacing. The spark plug itself will be screwed directly into the metal, and a screw is threaded into the metal for adjustable spacing(3-6mm).



A -7kV pulse causes the HV electrode to spark to the center electrode. The center electrode arcs to the outer(ground) electrode and in this way shorts the HV to ground.

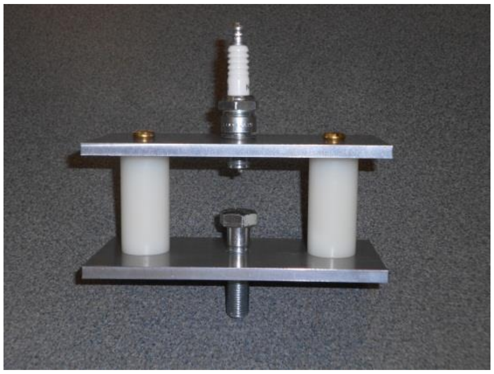


Fig. 22 Symbolic Spark Gap Design

Fig. 23 Spark gap

5 Gas System

5.1 Characterisitcs

Noble gases are used because they are stable and do have not an excessively high ionization potential[5]. They are either used separately or in various ratios. Most often seen with abundance of Helium or Neon [1][2][4]. Argon can also be used predominantly but that is rare. It is more often used with other gases like Ar/He, Ar/Ne or Ar/He/Ne [5]. Ratio from 0.01% - 10% Ar proved effective but 10% was considered optimal in at least one case [15]. Other gases or vapors can be added for UV damping purposes but that will be discussed in detail later. As with the other choices it is a balance between performance and economy.

Neon is the most expensive gas, argon is the cheapest option. Neon is generally considered the premium option due to its high first townsend coefficient (the mean number of ionizing collisions per unit drift length) which minimizes spark formation time. So neon is the best option when the spark chamber is being used to make measurements and observations. Helium follows as second best and argon the least. Pure argon requires the highest voltages to produce a spark, whichis not very visible with regard to intensity and color [6].

Breakdown voltages for Ar and He differ slightly from Paschen's Law[24][25] on breakdown voltages. We can though assume that the required voltages for our apparatus is lower due to the ionized path from the charged cosmic-ray. But knowing exactly how much lower is difficult to say. Having a small amount of argon with helium proved to increase chamber efficiency due to the extra electrons in the avalanche resulting in a higher first townsend coefficient [5][15].

Vacuuming the device can serve to be problematic. It depends on the design but the great pressure exerted on the chamber due to the vacuum could easily damage the device. Running argon through the chamber would be an ideal and cheap way for clearing. That is also an good way to get argon into the gas mix if a non-recycle gas system is used and test the effects of certain He/Ar ratios. Flushing of at least several volumes is necessary for good efficiency. In one case, three volume flushes left 5% air while flushing seven volumes left only 0.09% air [5]. Having the least amount of air is crucial for efficiency.

The major downside to using helium is that helium is prone to leak so making the chamber airtight will be more challenging and more important. The helium can also damage the sensitive scintillator equipment that will likely rest above the chamber

The discharge color of gases depends on several factors though it doesn't change dramatically with regard to those factors. Current density, electric field, temperature, pressure, gas purity and the envelope are the biggest ones [22]. We can expect helium to be purple to pinkish, Neon red or orange, most likely red in our case, Argon purple to teal. Adding only a few percent of neon to helium will cause the gas mixture to glow with the characteristic red of neon [5], which could improve visibility.

5.1.1 Quenching Agents

Ultraviolet light can cause random and out of place sparks in the spark chamber, called spurious sparking. However, some gases or vapor hydrocarbon mixtures can be added to the gas mixture to combat this by acting as a quenching agent for UV light. The first solution is to use Freon Gas. Unfortunately Freon is very detrimental to the environment and there are some safety issues. The second solution is to use Butane, which is just as effective as Freon but without the environmental hazards. However, Butane poses even greater safety issues than Freon because of it easy computability. The final solution is to use alcohol vapor, specifically isopropanol. The addition of alcohol vapor to argon reduces spurious streamers and sparking, narrows and brightens the sparks and reduces the spark development time [15]. On the other hand since it is a vapor the gas mixture needs to be kept in motion at all times or else the vapor will condense inside the spark chamber. This requires the use of a more complicated gas system. A quenching agent may be necessary if spurious sparking is seen as an otherwise unavoidable characteristic.

Unfortunately Freon and Butane need to be premixed with whatever other gases are being used in the spark chamber. Alcohol vapor on the other hand can be mixed on the fly. Doing this requires a bubbler, where the gas mixture is inserted into a pool of alcohol with a rubber tube. As the gas bubbles through the alcohol it becomes vaporized. Calculations for vapor pressure of bubbled isopropanol can be found with a simple equation [23].

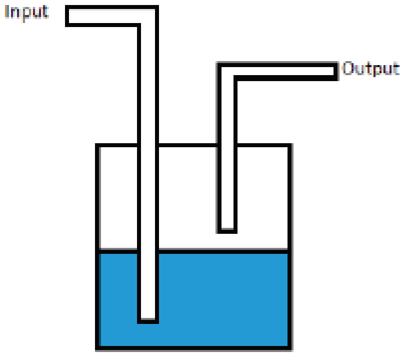


Fig. 24 Alcohol Bubbler

5.2 Gas System Design Options

In the simpler designs that are not completely isolated systems the spark chamber needs some kind of seal to prevent the gas mixture from escaping rapidly out the exhaust as well as to make sure that at no time oxygen is allowed into the system. There are two fixes to this problem, the first is to use a mass flowmeter at the exhaust and the second is to use a water bubbler.

Using a mass flowmeter gives you a lot of control over just how quickly you want to move the gas through the system. Unfortunately most flow-meters only work if the gas that's flowing through them is uniform; there are mixed-gas flow-meters however they add another additional cost. The alternative is to use a water bubbling system where the gas exhaust is output through a rubber tube into a tub of water and allowed to bubble through it. One can control how much back pressure the water exerts on the tube by changing the height of the water or how far down the rubber tube is beneath the surface of the water. The other advantage to using this system is that it is almost free; however it does require that the water in the tub remain at a constant level.

5.2.1 Option 1

The first design and the one that should be used for the first prototype is the simplest. It consists of hooking the gas tank directly up to the spark chamber and hooking a water bubbler or a gas flow-meter directly up to the exhaust. Unfortunately neither Freon Gas nor Butane Gas can be used with this system since there is nothing to filter it out before it reaches the exhaust which means these gases will be allowed to leak into the atmosphere uncontrolled. The purpose for the bubbler is both to watch flow rate and to make sure positive pressure is kept so oxygen does not contaminate the chamber.

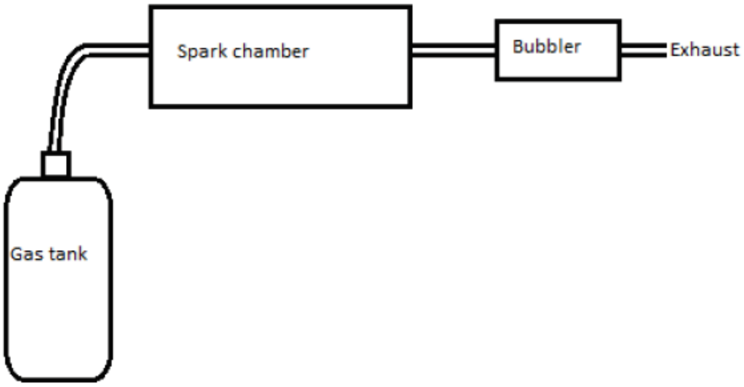


Fig. 25 Gas System Option 1 Diagram

5.2.2 Option 2

The second design is very similar to the first except that it includes a system for an alcohol bubbler. The intake of the alcohol bubbler is connected to the outlet of the gas supply system and its outtake is connected to the spark chamber. If this design is used a flow-meter cannot be hooked up to the outtake of the spark chamber because the alcohol vapor will interfere with the flow-meter’s ability to take proper measurements and the alcohol itself might be hazardous to the instrument. If a water bubbler is used, the result of mixing water and alcohol can be just as serious. Adding alcohol to the water changes its density with in turn changes the amount of back pressure being exerted on the gas tube leading into the bubbler which then changes the pressure inside the spark chamber. To alleviate these problems a dehumidifier, consisting of silicon crystals, is added in between the spark chamber and the pressure containment system. Unfortunately if Freon Gas or Butane Gas are used with this system, there is nothing to filter it out before it reaches the exhaust, these gases are allowed to leak into the atmosphere.

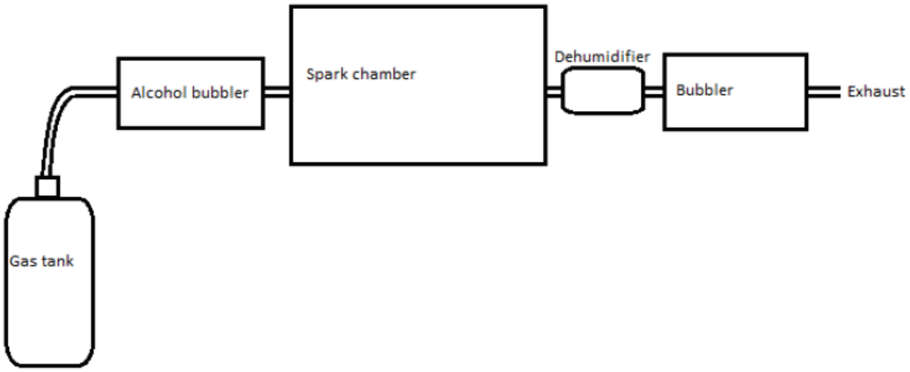


Fig. 26 Gas System Option 2 Diagram

5.2.3 Option 3

Leaks will be less constant if the gas is kept moving within the chamber. If gas costs are too high from constant replacement due to leaks, using a cycling gas system could reduce costs dramatically in the long run.

One simple method has the following components: Water tower, bell jar, dehumidifier, gas pump, valves, three way valve and tubes. Gas is allowed into the bell jar, with the top valve closed, until desired pressure is reached. The pressure needed can be calculated from the ideal gas law. The pressure in the bell jar can be calculated using the height of the water in the water tower. Then the intake valve is closed and the top valve opened. The dehumidifier makes sure no water vapor gets into the spark chamber. Once the gas has spread to the whole system the top valve is closed and the gas pump is used to keep the gas moving. It's hard to tell what the flow rate should be without be able to do experiments but a rate of 60 mL/min is a starting rate. The three way valve is obviously set so that the gas doesn't exit through the exhaust. When air is flushed out the three way valve is set the other way.

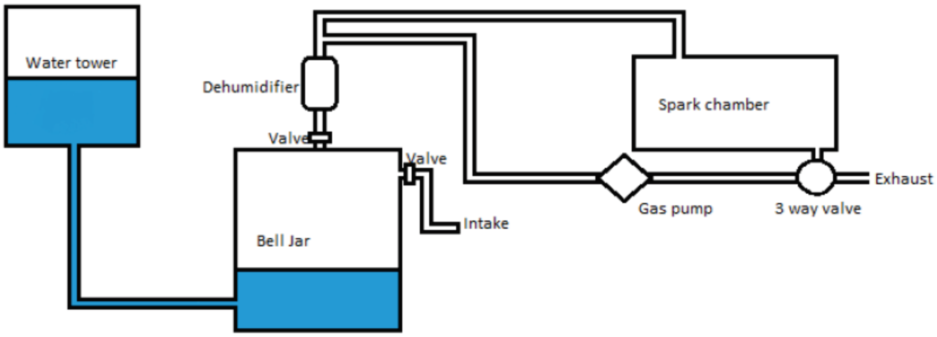


Fig. 27 Gas System Option 3 Diagram

5.2.4 Option 4

The final and most complex gas system design allows for recycling the gas while at the same time allowing for the utilization of alcohol vapor for UV absorption. It uses two water pumps to keep the gas current flowing which is necessary if alcohol vapor is going to be used. This is because if the gas is stagnant then the alcohol vapor will condense inside the spark chamber which could have disastrous consequences. While the pump on the left empties the left belltower the pump on the right fills up the right belltower. This pushes gas out of the left bell jar and suction pulls gas into the right jar, thus creating the current. After one bell jar is empty and the other is full the water pumps switch reversing the current of the gas.

The switching mechanism will be controlled by a timer and to make sure it functions properly we measure the amount of time necessary to fill up one of the bell jars from empty and use that amount of time for the timing mechanism. The dehumidifiers serve two purposes; first they remove any water vapor from the gas mixture as it leaves the bell jar and it removes any alcohol vapor before entering. Removing water vapor from the gas mixture is an absolute necessity since water causes a lot of problems if it gets inside the spark chamber. Removing any alcohol vapor before it contaminates the water is important too because if the alcohol mixes with the water it could potentially damage the water pumps and it would also change the amount of time required to empty or fill one of the bell jars which would mess up the timing of the water pump switch and the flow of the gas mixture.

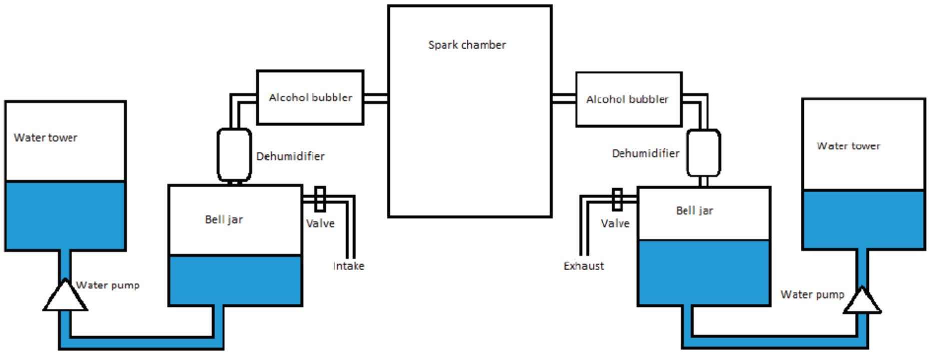


Fig. 28 Gas System Option 4 Diagram

6 Safety

The spark chamber design will have to be in compliance with Occupational Health & Safety regulations.

6.1 Gas Safety

The three different gases that are commonly used in a spark chamber each have one main risk. Helium, neon, and argon all cause asphyxiation, due to a lack of oxygen, when inhaled in excess. However, the density of helium and neon is lower than air. This allows for these two gases to naturally disperse throughout a room, eliminating the risk of inhaling too much at once. Unfortunately, argon does not have this convenience. The higher density of argon (air density 1.225 kg/m^3; argon density 1.784 kg/m^3) makes this gas more dangerous if a leak were to occur. A leak causes a buildup of Argon at the bottom of the display pit. Although it is not likely that this will occur, someone could potentially asphyxiate from the argon. These gases are all nonflammable, so there are no risks in having the gases present during spark formation.

Assuming a worst case scenario, where a person falls in the display and is knocked unconscious. It could be possible to asphyxiate on a thin two-inch layer of argon settled at the bottom of the display. Using the equation ideal gas law, there would need to be 2.61E-4 moles of argon in the display in order for risks to be present. The most common, and most likely, leak to occur in the display is from a pin-sized hole. A model for a leak through this kind of hole, Hagen Poiseuille Equation, is

Q = volumetric leak flow rate (cm^3/sec)
C = constant (defined during calibration)
d = diameter of pinhole (cm)
L = length of flow path (cm)
DP = pressure differential across flow path (kPascal)
μ = fluid viscosity (μPascal-sec)

$$Q = C \times \frac{d^4}{L} \times \frac{DP}{\mu}$$

For any holes larger than a pinhole, e.g. a crack or poor sealing around the edges of the chamber, the following equation can be used in order to calculate the volumetric leak flow rate.

(∂p/ ∂t) = pressure decay rate (kPascal/min)
V = volume inside chamber (cm^3)
P = gas pressure (kPascal)

$$Q = \frac{\partial p}{\partial t} \times \frac{V}{P}$$

The volumetric leak flow rate can be used to solve how long it takes until the volume of argon necessary for endangering a human leaks from the chamber. From a pin-sized hole in the chamber, the volumetric flow rate is equal to (2.58E-23)C (where C is found by calibration).

In order to follow the safety codes of Virginia Tech, the gas cylinder is stored in housing, out of the direct sunlight, to prevent expansion, and away from public access.

6.2 Spark Safety

Electromagnetic Pulses (EMP) are created after the spark formation. An EMP can be very harmful to electronic devices, such as computers, or more seriously, pacemakers. Having this display in a public place near numerous computers creates concern. In order to eliminate this concern, a faraday cage can be placed around the chamber. This faraday cage will act as a wall to the EMP and protect the computers in the laboratory from any damage caused by this display. A faraday cage can be simply made out of a sheet of aluminum with square cutouts or a wire mesh.

Although the faraday cage would be beneficial in the aspect of safety, it is not necessary to have. In order to show this, the limits of a pacemaker were compared to the high voltage and distance of our display. A 100 kV maximum is recommended for people with pacemakers around equipment with high voltage. It is also suggested that there is a separation of 6 kV/m. The spark gap will be enclosed in a metal box and has a maximum of 15 kV. The closest an observer can be to the spark gap is over 2 meters, leaving ample distance between the spark gap and the pacemaker [26]

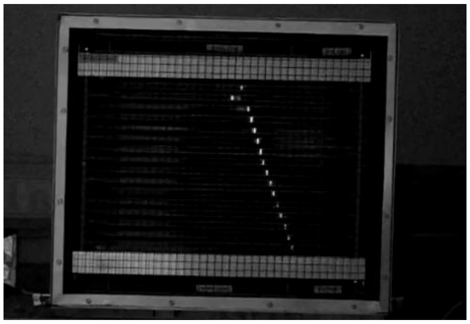


Fig. 29 Faraday Cage Surrounding a Spark Chamber [6]

When a spark gap is used, the oxygen and nitrogen in the surrounding air is ionized. These ionized molecules can reform into harmful molecules, such as O_3 and NO. Placing the display inside gives these harmful molecules no chance to disperse and dissipate in the atmosphere. These molecules present minor health hazards to the people near the spark gap. However, the spark gap in this demonstration is not continuously generating these ionized molecules and therefore the amount of harmful molecules present is minimal.

6.3 Maintenance

Safely fixing any malfunctions on the display is very important. There will be a “switch to ground” on the high voltage aluminum rod that can be turned on after the high voltage is turned off, discharging the capacitor bank. After doing this, the display will be safe and ready for any maintenance work necessary. As part of the OHS Guidelines a formal operations manual is to be created for the operating spark chamber.

7 Project Summary

7.1 Summary of Systems

Reference Number and Part	Description, Purpose, and Justifications for Cost
1. Airtight Chamber	Oxygen is a poison to spark formation. The Goal of an airtight chamber is to house the stack of electrode plates in a gas environment favorable to spark formation such as argon, neon, or helium. A box is constructed out of Lexan sheets. Five sides of the box will be cemented together with a bonding agent. A lip with spaced holes on the side panels allows the sixth side of the box to be screwed down on top. The O-ring cord stock fills a groove along the edge of the sixth panel. The combination of the bonded sides and O-ring creates an airtight seal.
2. Electrode Plates and Support Structure	The spacing between each electrode must be constant across the surface of each electrode. This will be achieved by running three Delrin rods through each electrode in the stack for stability. Between the electrodes are identical spacers cut from Delrin tubing. This supports the electrode stack while isolating the plates from each other with constant 1cm spacing. The bottom spacer is larger to keep the entire stack more isolated from the base of the airtight chamber. The structure will exist entirely inside of the airtight chamber. The electrode plates will be cut from 1cm thick 3003 aluminum alloy. Fig 2.
3. Trigger to Electrode Bridge	It is important to isolate the electronic components for the atmosphere of the air tight chamber. To achieve this, two threaded aluminum rods run through the base of the airtight chamber. The seal is maintained by self-sealing washers around the rod on each side of the of the Lexan bottom. The two rods run the length of the electrode stack, set some distance away from the stack. Outside of the chamber one aluminum rod is connected to the HV and spark gap. The other rod is grounded. Inside of the chamber the HV will be connected to alternating plates and the ground is joined to each plate by quick tab connections designed to fit on the notches of each electrode.
4. Scintillation and Coincidence	Two scintillation paddles with photomultiplier tubes detect muon occurrences above and below the electrode stack. A separate coincidence logic gate, detects events caused by a single muon passing through the chamber and both paddles. A signal is sent to the triggering circuit.
5. Gas System	The gas implemented inside of the spark chamber has a wide impact. The characteristics of concern are visibility, safety, HV requirements, leakage, and cost. The gas will be kept under a slightly positive pressure to ensure the absence of oxygen. This positive pressure as well as the initial evacuation and replacement inside the chamber will be measured by a gas flow meter or bubbling system.
6. Trigger and Spark Gap and HV supply	The trigger components consist of amplification circuit, a high voltage tolerance capacitor bank, a spark gap, and a high voltage supply. The electrical components are first modeled in PSPICE software.

Table 1 Summary of Spark Chamber Systems

7.2 Summary of Costs

This outlines some the components of the design that have yet to be finalized and purchased. It is the first priority of the next group to finalize a complete design and create a cost figure to propose a budget.

Reference	Item	Part Number	Supplier	Price per Unit	Quantity	Cost
Set Costs						
2	**Electrode Material and Machining Quote***	10016	Mountain Precision Tool	$22.15	40	**$886.00**
3	**20KV 3.3nF Ceramic Capacitor***		HV stuff	$21.63	19	**$410.97**
1	**Lexan Sheet 0.375" x 23.625" x 24"**	POLCE ST	Interstate Plastic		4	**$190.88**
2	**Delrin Tube 1" ID x 1.5" OD x 8 Foot**		Professional Plastics	$118.78	1	**$118.78**
1	**IP Shipping**		Interstate Plastic		~	**$61.88**
2	**Delrin Rod 1" Diameter**		Professional Plastics	$6.44	6	**$38.64**
1	**Lexan Sheet 0.375" x 24" x 24"**	POLCE ST	Interstate Plastic	$34.40	1	**$34.40**
1	**Lexan Polycarbonate Glue**	IPS40-PT	Ridout Plastics	$34.32	1	**$34.32**
3	**Aluminum Threaded Rod**	94435A346	McMaster-Carr	$16.42	2	**$32.84**
1	**Gray PVC sheet 0.5" x 24" x 24"**	PVCGE	Interstate Plastic	$27.01	1	**$27.01**
2	**PP Shipping**		Professional Plastics		~	**$24.95**
1	**Lexan Sheet 0.375" x 0.75" x 24.75"**	POLCE ST	Interstate Plastic		4	**$20.60**
1	**Gray PVC sheet 0.5" x 0.5" x 25"**	PVCGE	Interstate Plastic		4	**$16.52**
1	**RP Shipping**		Ridout Plastics		~	**$15.00**
2	**SS Shipping**		Stainless Supply		~	**$14.47**
1	**Gray PVC sheet 0.375" x 0.25" x 25"**	PVCGE	Interstate Plastic		4	**$14.00**
3	**Self Sealing Washer**	335-1067-ND	Digi-Key	$3.00	4	**$12.00**
3	**Female Tab Quick Disconnect 0.25"**	I855C	Repair Connector		100	**$9.99**
1	**O-Ring Cord Stock 10'**	31985435	MSC Industrial Supply Co.	$0.81	10	**$8.10**
3	**Digi-Key Shipping**		Digi-Key		~	**$6.98**
1	**PVC Cement Oatey 8oz.**		Local		1	**$4.44**
Estimated						
5	**Gas System**		~		estimated	$350.00
5	**Wooden Support Structure**		~		estimated	$150.00
7	**EMP Insulating Structure with Lock**		~		estimated	$50.00
					Set Costs	$1,982.77
					Estimated Costs	$550.00
					Projected Total	**$2,532.77**

Table 2 Summary of Costs

*The quote includes both the cost of the aluminum and the cost of machining.

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