Research and Development on RPC Detectors & Design and Construction of a Cosmic Ray Test Stand

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Abstract
This paper discusses the design and construction of Resistive Plate Chambers detectors. It also discusses the construction of a cosmic ray test stand for twenty glass Resistive Plate Chambers, the science and technology of Resistive Plate Chamber, and a brief background of the OFF-AXIS experiment.

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I. INTRODUCTION

A. Background

A large number of neutrino experiments have been initiated to probe and answer some specific questions about neutrinos. Despite these many experiments that answer some specific questions about neutrinos, many issues still remain unresolved. A collaboration of scientists at Fermi National Accelerator Laboratory (FermiLab), and other institutions are proposing a new neutrino experiment to achieve the following physics goals:

a. Observation of the transition $\nu_\mu \rightarrow \nu_e$
b. Measurement of θ_{13}
c. Determination of mass hierarchy
d. Search for CP violation in neutrino sector
e. Measurement of CP violation parameters
f. Testing CPT with high precision

The experiment, called the OFF-AXIS experiment, will share the newly constructed NUMI[1] beam for source of neutrinos with the MINOS[2] experiment, another neutrino experiment being initiated at Fermilab.

A 50,000-ton detector is being planned to be assembled for the OFF-AXIS experiment to achieve the experimental goals listed above. Resistive Plate Chamber (RPC) is one of the two calorimeters proposed for the OFF-AXIS detector the other calorimeter is scintillator. RPCs are detectors that are extensively used in Astrophysics and High Energy Physics, because of their ruggedness and affordability. The excellent features of RPCs are their very large signal, the reduced cost per unit area, a good time resolution in the order of 1 ns, an excellent and cheap readout system and construction free from damaging discharges. [1]. The reduced unit price is a factor that reduces cost considerably when the construction of a 50,000 kiloton detector is considered when compared with the cost of the scintillator option.

B. Project

As a summer intern, the author was assigned to a subdivision of the OFF-AXIS collaboration. This subdivision, which is headed by Adam Para, is concerned with Research and Development on Resistive Plate Chambers. Resistive Plate Chambers despite their relatively cheap price and robustness are not yet a perfected technology. RPCs are built on the same principle but not the same method, and construction varies from experiment to experiment. RPC construction is tailored to experimental needs. Also there are many misunderstood problems associated with construction and operation of RPCs. All the parts of an RPC assembly are required to be properly configured. From experience with previous use of RPCs, if a part is not well configured, the chance of this part rendering the whole RPC assembly useless is very high. Since RPCs are a viable option for the OFF-AXIS experiment calorimeter, there was a need for a detailed study of RPCs from construction stage to operation stage. The subdivision was faced with the following task:

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[1] NUMI is an acronym for Neutrinos at the Main Injector, a facility built to produce neutrino beam for the MINOS experiment.

[2] MINOS experiment is an acronym for Main Injector Neutrino Oscillation Search, is an experiment that will probe the oscillatory effect of muon neutrinos.

- Designing and Building prototype RPCs from scratch
- Designing and Building a Cosmic Test Stand for various conditions that might affect the operation of RPCs, using the prototype RPCs.
- Testing RPC modules supplied by Virginia Technological University for leaks and efficiency.
- Testing of some RPC components.

This paper focuses on theory, operation and construction of RPCs and the construction of a cosmic ray experimental setup for RPCs.

II. RPC: THEORY AND OPERATION

A. Fundamentals of a Resistive Plate Chamber.

An RPC is a detector that uses ionization of gaseous molecules to detect tracks of charged particles. The basic components are a cuboid container, an anode, a cathode and, a mixture of gases. The cuboid container is designed in a way to provide the right volume for a gas mixture and at the same time provide the right geometry for attachment of an anode and cathode. The anode and cathode are attached to the two parallel surfaces of the cuboid. A set up is shown in Fig 1.

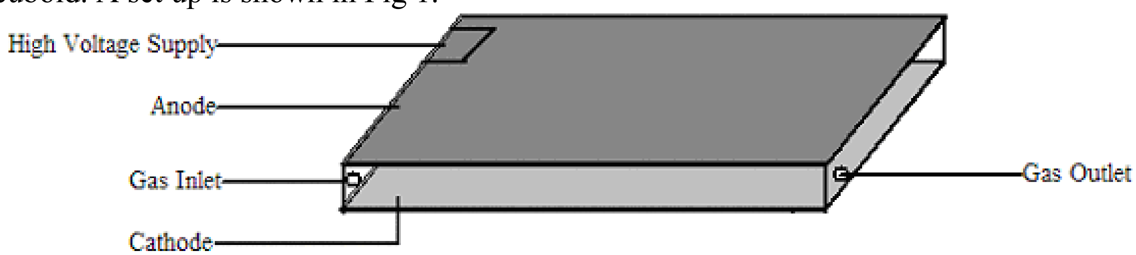


Fig 1. Diagram of a basic RPC

A High Voltage is used to supply an Electric field in the direction from the anode end to the cathode. In some constructions, a spacer stick is used to ensure the distance d in Fig 2 is constant between the anode and cathode. This in turn will provide a uniform electric field E over the entire volume.

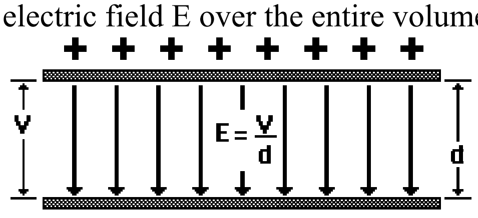


Fig 2. Diagram depicting electric field line movement

B. Mode of Operation.

A charged particle entering the container knocks of an electron from an atom of a gas, thereby creating an ion and electron pair. The electron and ion created are accelerated towards the anode and cathode respectively. RPC can be made to operate in two modes, depending on the applied voltage and operating gas mixture: the avalanche or streamer (breakdown) mode. In the avalanche mode, the voltage applied creates an electric field strong enough to accelerate freed electrons to an energy where they are capable of ionizing other gas molecules in the container. The numbers of secondary electron-ion pair produced is proportional to the number of primary electrons that induced the avalanche. This avalanche of electrons is picked by a readout system for conversion into signals at the electronic end.

The streamer mode is a mode with a higher operating voltage than that of the avalanche mode. At this mode the secondary ionizations, caused by photons emitted by excited molecules, which travel to other part of the container to cause further ionization, are so large that the space charge created distorts the electric field, eventually causing a discharge in the detector gas. A quencher gas is added to the original detector gas to control and localize this discharge. A readout system picks up the signal in a fashion similar to the avalanche mode. The OFF-AXIS RPCs will be operated in the streamer mode.

C. Gas Mixture (Streamer Mode)

The choice of filling gas is determined by many factors including; low working voltage, high gain, good proportionality and high rate capability [2]. Factors relating specifically to the gas are:

- Noble gases are chosen over other gases because they require the lowest electric field for formation of avalanche. Argon is preferred over the rest of the noble gas because of its low cost and high specific ionization factor.
- A Polyatomic gas such as, Isobutene, Methane or Boron Trifluoride are added to act as quenchers. They perform this function by absorbing the radiated photons and dissociating their energy through dissociation or elastic collision.
- Electronegative gas like Freon (CF_3Br) is sometimes added to increase the gain of the readout detector. They perform this function by absorbing photons emitted by the electrons and by capturing the electrons themselves.

D. HV

The voltage required for operation of RPCs in an experiment such as the OFF-AXIS experiment, which is going to be operating in the streamer mode, is around 8000-9000V. A simplified explanation is given below for this requirement.

The atoms of the detector gas require a certain ionization energy that needs to be overcome before an electron can be released. The electron released is accelerated a distance Δs towards the anode, before it collides with another gas atom. If an electron has energy up to the ionization energy of the atom it will ionize the atom and set another electron free. In this process, the original electron loses its energy and it will be accelerated again from zero energy with the second electron, if it was successful in releasing it. The two electrons in turn release a total of two other electrons, making the total of free electrons four. This process goes on until an avalanche is formed. For an avalanche to be formed, the right amount of energy is needed by the free electrons to knock off more electrons. The energy is a function of the electric force F and the distance Δs traveled by the electron. The electric force F is a function of the Electric field, which is directly a function of the voltage and distance between the anodes.

$\text{Energy}=F\Delta s$ Eq 1. ($F=eE$) Eq 4.

$\text{Energy}=eE\Delta s$ Eq 2.

$\text{Energy}=e\Delta V\Delta s/d$ Eq 3.

Where e is an electron charge, V is voltage and d is distance between anode and cathode.

From previous work with RPCs all over the world, it is known that the maximum efficiency of the RPC detectors is obtainable at around 8000V to 9000V. Application of a higher voltage does not have any effect on the number of electrons produced. This is in part due to the effect of the quencher gas, which enforces a plateau on the number of electrons obtainable as shown Fig 3. As mentioned earlier, spacers are used to ensure a uniform electric field.

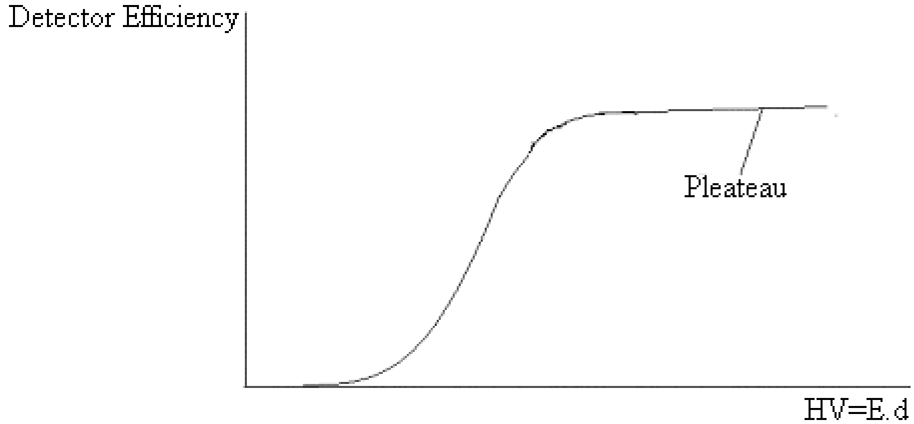


Fig 3. Plot of numbers of RPC efficiency vs. HV

E. Detection System.

As the electrons travel toward the anode, they radiate electromagnetic waves. The waves are picked up inductively at the cathode and at the anode by a readout system. The readout system is a board with two different surfaces, one for signal transmission and the other side for signal protection. It is basically a capacitor-like setup; with two plates separated by a dielectric material.

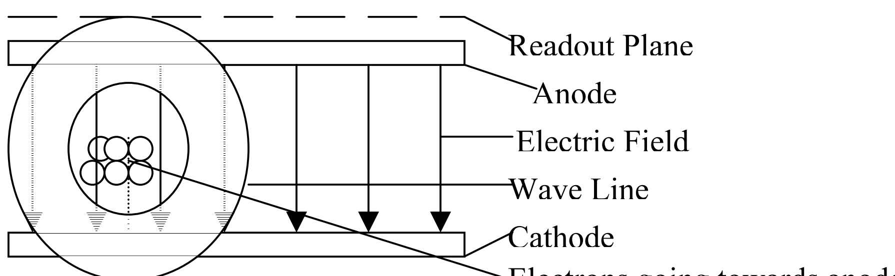


Fig 4. Schematics illustrating pickup of signals

F. Glass RPC Overview.

The type of RPC proposed for the OFF-AXIS experiment is the glass RPC. Fig 5 shows the schematic of a glass RPC layout. Two parallel glass plates enclosed in edgers (varies according to construction) constitute the mainframe of the RPC. A resistive layer is applied directly on the outer side of both glass plates. These layers act as the anode and cathode. The resistive paint serves two functions; it is conductive enough to serve as the anode and cathode, and it is resistive enough to prevent itself from conducting away signals from the signal pickup configuration. Also shown is the spacer required for uniform electric field. Fig 6 shows the equivalent circuit of an RPC module. At low voltages the gas mixture is insulating, the current passes through the spacer as seen Eq 5. At high voltages the gas mixture is shorted out because of the discharge and this make the gas mixture to act effectively as a conductor. As a result of the effective voltage is applied on the glass electrodes as seen in Eq 6, which results in a higher current.

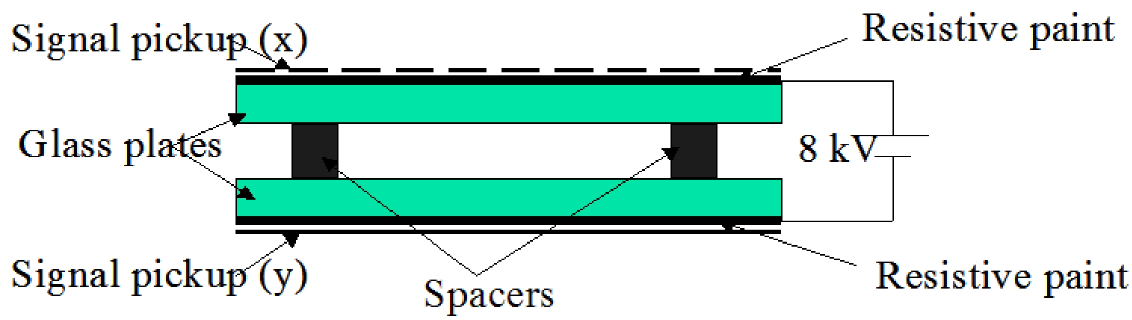
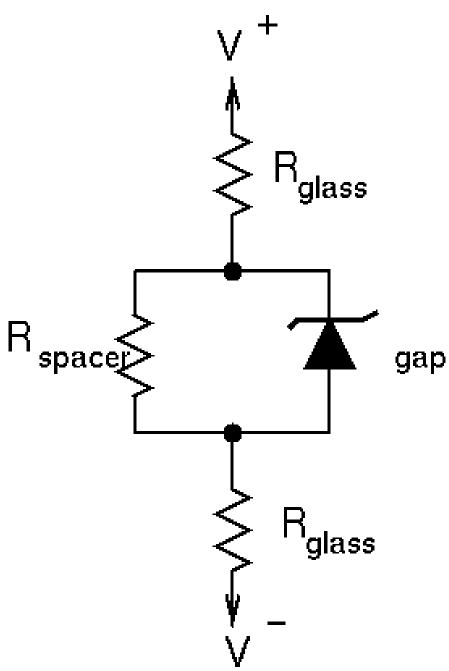


Fig A.5 Glass RPC layout



Low voltage

$$R_{gap} \approx \infty \qquad \text{Eq 5}$$

$$\frac{dV}{dI} = R_{spacer} \qquad \text{Eq 6}$$

High voltage

$$R_{gap} \approx 0 \qquad \text{Eq 7}$$

$$\frac{dV}{dI} = R_{glass} \qquad \text{Eq 8}$$

Fig 6 Electrical circuit representation of Glass RPC

III. CONSTRUCTION OF RPCs

A. Frame

The components of the prototype RPC frame built consist of two 1square foot glass plates, spacers, edgers, gas connectors, and *3M 2216* translucent epoxy glues. The pair of glasses are first washed and dried to make them free of streaks and other potential contaminants. The glass plates are then glued to each side of four edgers as shown in Fig 7. A spacer such as the one depicted in Fig 8 is glued between the glass plates to give a precise distance of 2mm, required for the uniform electric field between the glass plates. Two spaces are created on one of the four edgers for fixation of two gas nozzles, as shown in Fig 9 and Fig10.

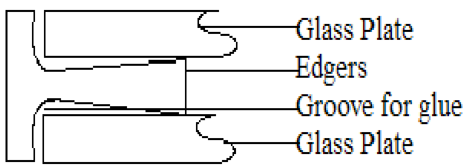


Fig 7. Edger to Glass joint.

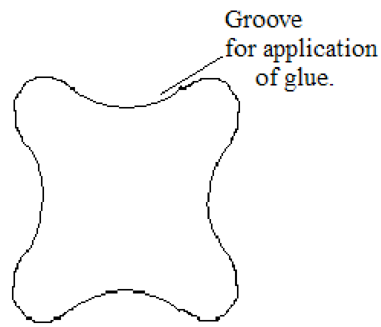


Fig 8. Cross sectional profile of a spacer.

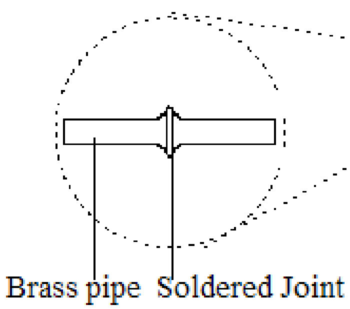


Fig 9. Gas Nozzle.

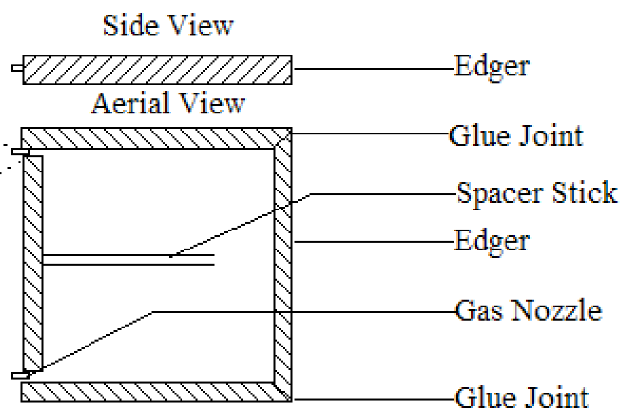


Fig 10. RPC frame.

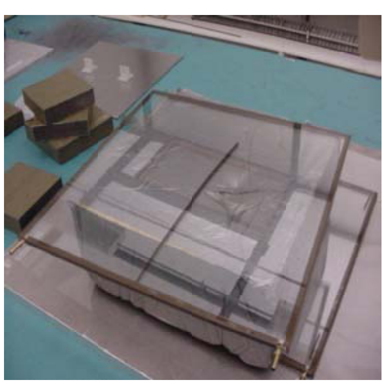


Fig 11. Photograph of Finished RPC frame

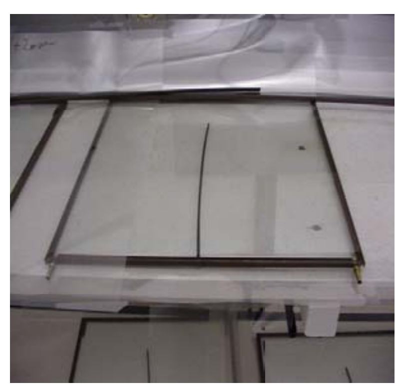


Fig 12. Finished RPC frame

B. Gas Nozzles

The gas inlet pipes depicted in Fig 9 were built from two small brass tubes. One of the brass tubes was flattened to about 1.80mm halfway, so that it can fit into the 2mm space between the two glass plates. This part was then meticulously soldered to the other piece of flattened brass to form a single unit gas nozzle as shown in Fig 13.

Fig 13. Gas Nozzles.

Fig14. Nozzle attached to frame.

C. Electrode

"SPRAYON S002004 DRY GRAPHITE " aerosol was the resistive layer used to serve as both cathode and anode. It was sprayed in uniform layer over the glass, to get a finished surface as shown in Fig 16. The electrode has an average surface resistivity value around 3.667MΩ/m

D. Signal Readout

The readout pads for the RPCs were made from home insulating foam board and copper foil. The boards were cut into 1 square foot. The copper foils were also cut into 1 square foot. The copper squares were then glued to the foam squares using 3 M SUPER ADHESIVE SPRAY aerosols.

Fig. 15 Photograph of a readout pad.

Fig.16 Photograph of RPC with electrode layer

E. Overall Specification

The table below gives the overall specification of the prototype RPC.

Quantity	Prototype RPC dimension
Length	12.25in
Breadth	12.25in
Height	6.60mm
Electrode Surface Resistivity	3.667MΩ/m
Gap (Anode to Cathode)	2mm

IV.DESIGN OF A COSMIC RAY TEST STAND

A. Experimental Purpose.

An experiment was proposed to study the effect of operational conditions on RPCs. The experiment will test various conditions such as temperature effect, pressure effect, e.t.c on RPCs. The main purpose of this setup is to learn and understand the various factors that might effect the operations of bigger RPCs that are to be built in the future. Twenty RPCs, which were built, were divided into five groups of four. Each group will be tested for a certain condition.

B. Experimental Stand Design

The following factors were put into consideration when the experimental rack was designed:

- Each group of four RPCs had to be stacked separately, from the other group.
- Also four scintillators were needed to define the trigger for the RPCs Data Acquisition System.
- The scintillators had to be properly aligned with the RPCs so that they define an adequate area for cosmic events.

The rack configuration in Fig 17 was designed to meet the above criteria. The frame was designed for assembling from unistrut metal. It has six slots; the five top slots will house the five groups of four RPCs and the bottom slot for two scintillators. The other two scintillators will be placed on top of the crate.

In the final construction, the design was slightly modified. A standard crate was used instead of the unistrut frame crate. Also the dimensions in Fig 17 were slightly varied. The finished product is shown in Fig 18.

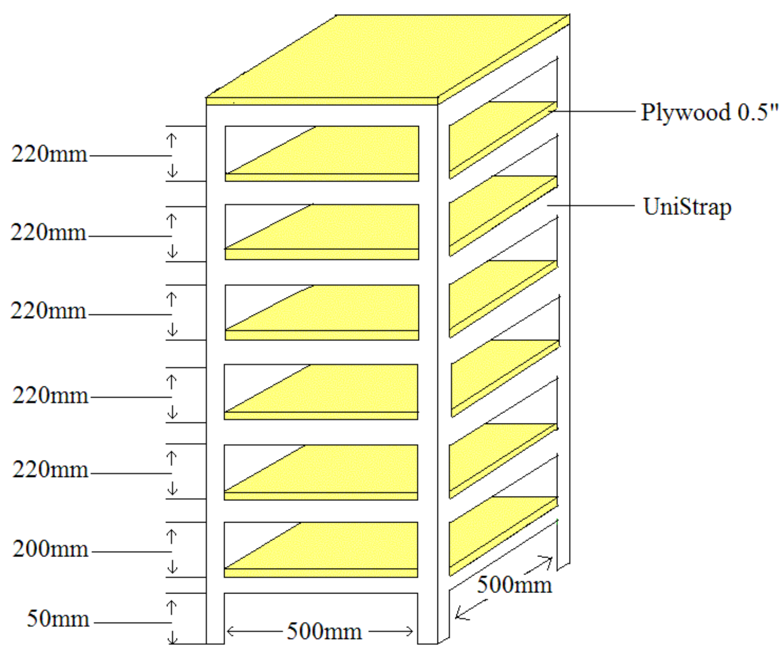


Fig 17. Design diagram for experimental rack.

Figure 18. Photograph of constructed rack

C. Design of Gas System

The diagram shown in Fig 19 is the schematic for the gas distribution system designed for the input and output of gas for the twenty RPCs System.

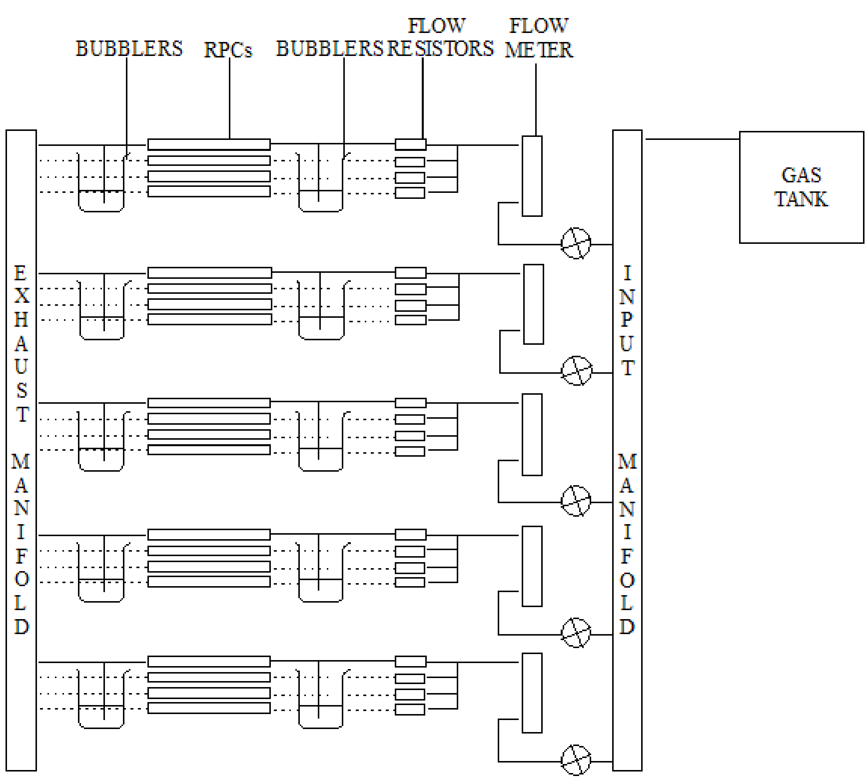


Fig 19. Schematics of Gas Distribution System.

The components of the gas system are explained below:-

- Bubblers: For balancing the changes in atmospheric pressure exerted on the Resistive Plate Chambers, in order to avoid damages to the Chambers.
- Flowmeter: A gauge meter, for physically measuring the rate of flow of gas through the RPCs.
- Flow Resistor: A narrow capillary tube of about 200µm inner diameter, which takes away pressure from an RPC. It acts by exerting a lot of pressure on the gas as it flows through it narrow capillary, there by leaving little pressure to be exerted on the RPC
- Input and Exhaust Manifold: Tubes for the intake of gas and outtake of gas to and from the twenty Resistive Plate Chambers.

Fig 20 shows the design of the panel for the fittings of the components named above.

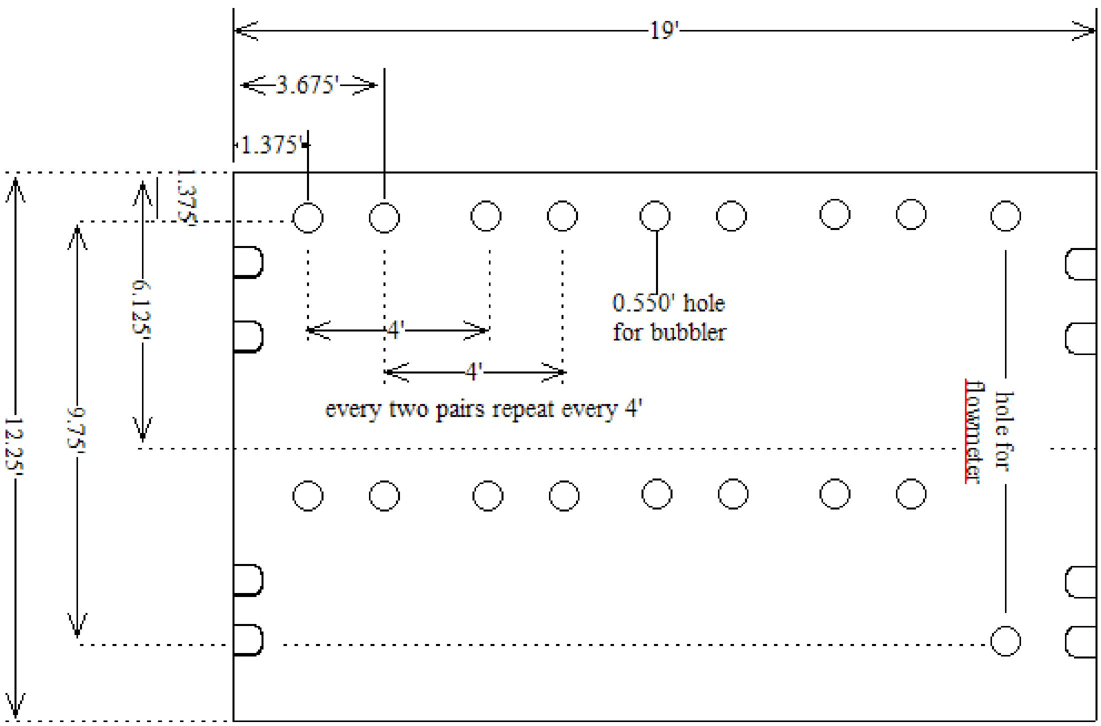


Fig 20. Design of panel for fitting of gas system components.


Fig 21: Finished Gas Distribution Panel.

D. Electronics

Charged particle events are used to induce signal events in the twenty RPCs. Cosmic particles are freely available in the atmosphere, so they provide a good source for signal events required for the test. The schematic of the electronics setup is depicted in Fig 22. The components are explained in the following paragraphs:

Four **scintillators** are used to define the area of the RPC plates where signal events will be read out. Two of the scintillators are placed on top of the rack and the other two are placed on the bottom of the rack as shown in Fig 23 .The overlapping area geometry of the four scintillators defines the area of event readout in the RPC. The coincidence of events in the four scintillators gives the trigger to the ADC gate for events to be read from the RPCs readout.

The **discriminator** is a module that gives out a standard logic signal when the pulse height of the signal is greater than a certain threshold value. The discriminator allows low amplitude noise from the photo multiplier tube to be blocked away. The value of the threshold is adjustable and the width of the standard signal is also adjustable.

The **logic unit** acts as an equivalent of a boolean circuit for the standard pulses it receive. It performs the AND operation on the pulses. So it performs a four fold AND operation on the pulses from the four scintillators, A.B.C.D . This is done to ensure that events are being read only from the defined area of RPCs

The analog to digital converter (**ADC**) converts the signal from the RPCs readouts into an equivalent digital form. The digital data is then sent to the computer for further analysis. Embedded in the ADC module is a **Linear Transmission Gate (Gate).** The gate is used to control input into the ADC. When the gate receives a standard logic pulse from the coincidence unit, it allows the ADC channel to intake signals from the RPCs readouts.

Look at Me Module (**LAM)** informs the computer to start taking data from the ADC.

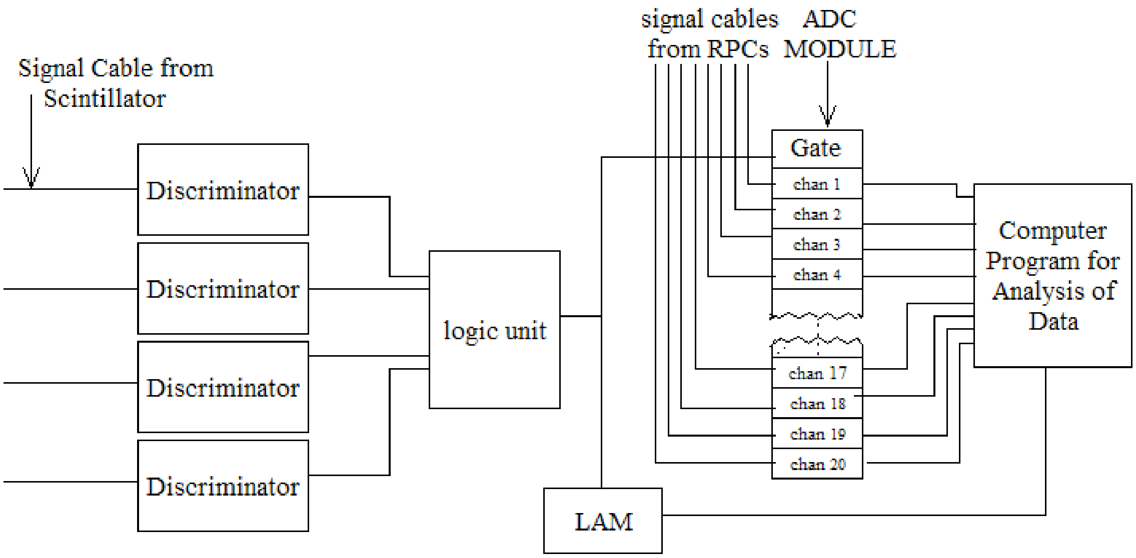


Fig 22. Layout of Electronics Path.

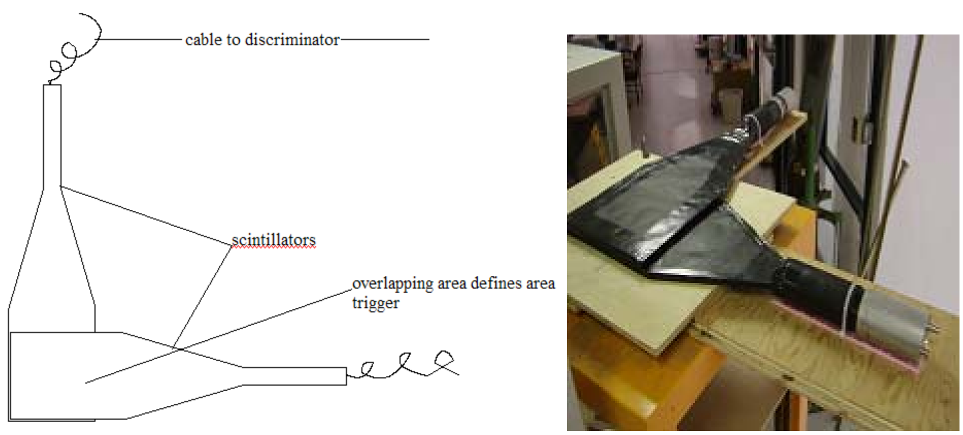


Fig 23. Arrangement of scintillators for events area definition.

E. DAQ

The ADC and LAM are CAMAC[3] modules, housed in a CAMAC crate. The ADC in conjunction with the LAM sends event data to the computer for processing and storage. The computer end requires a higher-level programming language to call functions, provided by the CAMAC supplier, coded in assembly language. A high level program is needed to call these functions in order to perform operations on the CAMAC module. These acquisition programs are most of the time portable from one computer to the other.

The acquisition program for the experiment was obtained from a pre-existing acquisition program writing in FORTRAN and C. The pre-existing acquisition program

[3] CAMAC is a modular system, which acts a standard interface between electronics and the computer that process data received from them.

was designed to read four channels. The program was modified to read twenty channels. A copy of the DAQ program is available in the appendix.

V. CONCLUSION.

As of the time of this writing most of the objective of this group has been achieved; twenty RPCs have been configured and built; the test rack, gas system, electronics and DAQ for the proposed experiment have been properly configured. The various configured parts of the experiment are now being assembled and data collection will begin in the very near future.

VII. ACKNOWLEGDMENTS

I would like to express my profound gratitude to the following people: Adam Para and Valeri Makeev for their time and patience in explaining the details and physics behind my project; Dr Davenport for his assistance in the development of this paper; The SIST committee for giving me another chance to participate in the SIST program; The Almighty God for the gift of knowledge and understanding.

VI. REFERENCES

[1] P Fonte, "Applications and New Developments in Resistive Plate Chamber" November 2001
[2] Leo, Williams, "Techniques for Nuclear and Particle Physics Experiment" Berlin Germany:Springer-Verlag 1987.
[3] Amoda, Oluwaseun, "Design of Readout System for a Resistive Plate Chamber" Batavia, Illinois, August 2002.
[4] The NuMI Facility and the MINOS Experiment, http://www-numi.fnal.gov/, Aug 01 2003

VIII. Appendix

A. 20 Channel Configuration File.
A configuration file that reads a total of 20 channels from two ADC modules.

```
*
*
*  Comment line start with *
*
*  commands are of the form
*        F:func C:crate N:slot A:subaddr
*        WQ:wait between Q  T:tries before Q error (0 for infinity)
*        R:repeat entire function W:wait between functions
*        E: no Q=fatal?  DO:save data? (2 for allways, 1 for Q=1)
*        DI:input data;
*        MXN: max slot (auto increment)  WN:wait slot increment
*        MXA: max subaddress (auto increment)  WA:wait subaddress increment
*
*  there must be no space between : and preceding or following parameter
*
*  Definitions are of the form
*              TAG = command;
*
*  Lines not terminated with ; are assumed to continue
*
*  AP 08/04/03 - This config file is for reading out 20 channels of ADC
*                No TDC.
*
*

  CRATE1 = 2;

  LAM_SLOT = 12;

  LAM SELECT = F:16 C:[CRATE1] N:[LAM_SLOT] E:1 A:0 DI:1;
  LAM ENABLE = F:28 C:[CRATE1] N:[LAM_SLOT] E:1 A:0;
  LAM POLL = F:8 C:[CRATE1] N:[LAM_SLOT] T:0 E:1 A:0;
  LAM READ = F:1 C:[CRATE1] N:[LAM_SLOT] T:1 E:1 A:2;

  ADC_SLOT = 16;
  ADC_CHAN0 = 0;
  ADC_CHAN1 = 1;
  ADC_CHAN2 = 2;
  ADC_CHAN3 = 3;
  ADC_CHAN4 = 4;
```

```
ADC_CHAN5 = 5;
ADC_CHAN6 = 6;
ADC_CHAN7 = 7;
ADC_CHAN8 = 8;
ADC_CHAN9 = 9;
ADC_CHAN10 =10;
ADC_CHAN11 = 11;

ADC_SLOT2 = 17;
ADC_CHAN0 = 0;
ADC_CHAN1 = 1;
ADC_CHAN2 = 2;
ADC_CHAN3 = 3;
ADC_CHAN4 = 4;
ADC_CHAN5 = 5;
ADC_CHAN6 = 6;
ADC_CHAN7 = 7;



ADC CLEAR = F:9 C:[CRATE1] N:[ADC_SLOT] A:0 E:0 ;
ADC CLEAR = F:9 C:[CRATE1] N:[ADC_SLOT2] A:0 E:0 ;
ADC READ0 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN0] E:0 DO:2 ;
ADC READ1 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN1] E:0 DO:2 ;
ADC READ2 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN2] E:0 DO:2 ;
ADC READ3 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN3] E:0 DO:2 ;
ADC READ4 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN4] E:0 DO:2 ;
ADC READ5 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN5] E:0 DO:2 ;
ADC READ6 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN6] E:0 DO:2 ;
ADC READ7 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN7] E:0 DO:2 ;
ADC READ8 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN8] E:0 DO:2 ;
ADC READ9 = F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN9] E:0 DO:2 ;
ADC READ10= F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN10] E:0 DO:2 ;
ADC READ11= F:0 C:[CRATE1] N:[ADC_SLOT] A:[ADC_CHAN11] E:0 DO:2 ;
ADC READ12 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN0] E:0 DO:2 ;
ADC READ13 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN1] E:0 DO:2 ;
ADC READ14 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN2] E:0 DO:2 ;
ADC READ15 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN3] E:0 DO:2 ;
ADC READ16 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN4] E:0 DO:2 ;
ADC READ17 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN5] E:0 DO:2 ;
ADC READ18 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN6] E:0 DO:2 ;
ADC READ19 = F:0 C:[CRATE1] N:[ADC_SLOT2] A:[ADC_CHAN7] E:0 DO:2 ;
ADC LAM TEST = F:8 C:[CRATE1] N:[ADC_SLOT]  A:0 WQ:10000  T:1  E:0;
ADC LAM TEST2 = F:8 C:[CRATE1] N:[ADC_SLOT2]  A:0 WQ:10000  T:1  E:0;

TDC_SLOT = 8;
```

```
  TDC_CHAN = 0;

  TDC CLEAR = F:9 C:[CRATE1] N:[TDC_SLOT] A:0 E:1 ;
  TDC LAM TEST = F:8 C:[CRATE1] N:[TDC_SLOT]  A:0 WQ:10  T:10000  E:1;
  TDC READ = F:0 C:[CRATE1]   N:[TDC_SLOT]  A:[TDC_CHAN] T:1 E:1 DO:2 ;


RUN INI:;

  [LAM SELECT] ;

EVT INI:;

  [ADC CLEAR] ;
  [LAM ENABLE] ;
  [LAM POLL] ;
  [LAM READ] ;

TRIGGER: 1 0;

      [ADC LAM TEST];
      [ADC LAM TEST2];
      [ADC READ0];
      [ADC READ1];
      [ADC READ2];
      [ADC READ3];
      [ADC READ4];
      [ADC READ5];
      [ADC READ6];
      [ADC READ7];
      [ADC READ8];
      [ADC READ9];
      [ADC READ10];
      [ADC READ11];
      [ADC READ12];
      [ADC READ13];
      [ADC READ14];
      [ADC READ15];
      [ADC READ16];
      [ADC READ17];
      [ADC READ18];
      [ADC READ19];
```