Development and Characterization of MRPC for Indian based Neutrino Observatory †

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Abstract

This paper describes the construction and working of a Multi- Gap Resistive Plate Chamber (MRPC) to be used in the Indian based Neutrino Observatory (INO). The MRPC provides better timing resolution when compared to the single gap RPC. The MRPC was made primarily out of glass, due to its high resistivity and economic feasibility. The mode of operation is the avalanche mode. With the help of a dedicated data acquisition system, the I-V characteristics, noise rate, efficiency and timing resolution of the detector were collected and analyzed.

1. Introduction

Neutrino mass and neutrino oscillation is a relatively new phenomenon. The Indian based Neutrino Observatory plans to study atmospheric neutrinos with an Iron Calorimeter (ICAL) detector. Single gap RPCs have been optimized to be the active detectors for ICAL. The goal of the R&D of a Multi Gap resistive plate chamber was to provide a better timing resolution and stable efficiency plateau while keeping the advantages of a single gap RPC.

1.1 Indian based Neutrino Observatory

Of the many global endeavors to study neutrinos, the Indian Based Neutrino Observatory (INO) is India's very own effort to study this particle. INO is a multi-institutional collaboration with an aim to build a world class underground laboratory at Pottipuram in West Bodi hills of Theni District of Tamil Nadu. A rock cover spanning 1.2 km housing a facility solely dedicated to non accelerator based high energy and nuclear physics. The primary aim of INO is to study neutrino oscillation theory along with mass hierarchy of neutrinos. The INO project will also host other experiments like the Neutrino-less double beta decay (NDBD) which will investigate whether the neutrino is a Majarona or Dirac particle.

Fig1.1: INO site at West Bodi hills near Madurai

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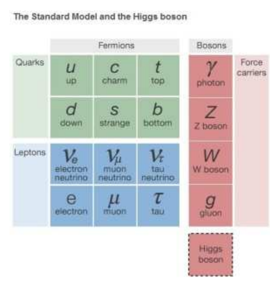
1.2 Neutrino oscillations and the need to study them

Neutrinos were first postulated by Wolfgang Pauli in 1930 to explain the apparent non-conservation of energy taking place in nuclear beta decay. Enrico Fermi then coined the term *neutrino* in 1934 to describe these evasive particles where the Italian syllable *–ino* means ‘small neutron. Due to such weak interactions neutrinos (mediated by the heavy $W^{\pm}$ and Z^0 bosons) can pass through ordinary matter undetected at low energies. The Standard Model holds that one neutrino (say the electron neutrino) cannot convert into another flavor (say the muon neutrino) in order to conserve lepton flavor quantum number. However, recent observations suggest the possibility of neutrino mass and neutrino oscillations from one flavor to the next. Neutrino oscillation is a quantum mechanical phenomena in which the neutrino changes state as it propagates. In 1957, Bruno Pontecorvo introduced the concept of neutrino oscillation based on a two-level quantum system [1]. The two states, the mass and flavor states are connected by a unitary matrix. This phenomenon arises only if:

1. The neutrinos are massive and non-degenerate. 2. The mass eigen states of the neutrinos - ν_1, ν_2 - are different from the flavor eigen states - ν_α, ν_β in case of two flavor neutrino mixing.

$$\begin{bmatrix} \nu_\alpha \\ \nu_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$



(Left) Fig 1.2: The equation relating flavor eigen states ν_α, ν_β with mass eigen states ν_1, ν_2 involved in two flavor oscillations.
(Right)Fig1.3: The Standard Model showing fundamental particles and their respective force carriers.

Recent experiments on neutrinos conducted in different parts of the world (especially the Super-Kamiokande and SNO experiments) strongly support the oscillation of neutrinos from one flavor to the next. Observations also affirm that neutrinos are massive and that the flavor oscillations are related to the mass squared difference of neutrinos involved in the mixing. The sources of neutrinos include furnaces of stars, supernovae, Earth’s atmosphere and if one goes back in time, the Big Bang. These elusive particles hold secrets not only to the beginning of the universe but could also lead to the possible extension of the Standard Model.

1.3 Iron Calorimeter at the Indian based Neutrino Observatory

The INO project includes the construction of an Iron Calorimeter detector (48m x 16m x 14.5m) which consists of 5000 tons of magnetized iron plates with provision to insert Resistive Plate Chambers (RPCs) in the gaps as active detectors. The ICAL will be subdivided into three modules of 16m x 16m each. The total number of 2m x 2m RPCs is estimated to be around 28,000.

The ICAL will be used primarily as a detector for atmospheric neutrinos. The neutrinos (and anti-neutrinos) on interaction with the iron slabs will disintegrate into charged muons and hadrons. A uniform magnetic field of 1.3 T will ensure charge discrimination of muons. The Resistive Plate Chambers used will be of the Single Gap variant with the possibility of using Multi-Gap RPCs for trigger mechanism.

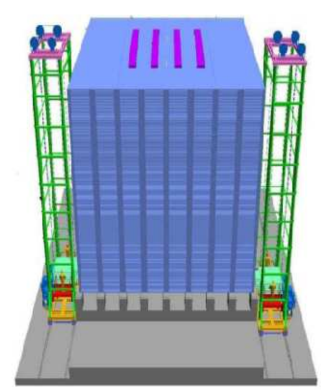


Fig1.4: Schematic view of one ICAL detector module with RPC handling trolleys.

2. Single Gap RPC, the active detector in ICAL

Based on years of neutrino detection study, it was concluded that the Resistive Plate Chamber is the most effective and economically feasible option. The R&D team at TIFR has created several working small scale models of Single Gap RPCs with encouraging results. The following is an account of the construction and working of the Single Gap RPC to be used in the INO project.

Single Gap Resistive Plate Chambers are parallel plate gas detectors, the anode and cathode of which are made of a highly resistive material such as glass (or Bakelite). These electrodes are in turn connected to a high voltage power source to create an intense electric field in the gas gap between them. A graphite coating on the external electrodes ensures uniform application of this high voltage. The two electrodes are separated by polycarbonate cylindrical spacers thereby maintaining a single gas gap. The gas mixture consists of Isobutane (4.2%), SF_6 (0.3%) and electronegative Freon (95.5%). This gas composition prevents the formation of streamers by absorbing photons while ensuring free flow of electrons. The electric pulses generated by the ionization of the gas are induced on copper pick up strips on the external surface of electrodes separated by a thin Mylar sheet. The mode of operation in this RPC is the avalanche mode. The incoming radiation is followed by propagation and multiplication of electrons akin to an avalanche effect. At large gas gain, this effect influences the electric field in the gas gap and ultimately the electron's propagation itself (space charge effect). The electric signals produced by the ionization are then discharged by the copper pick up strips on either electrode and the information is then transmitted to a data acquisition system.

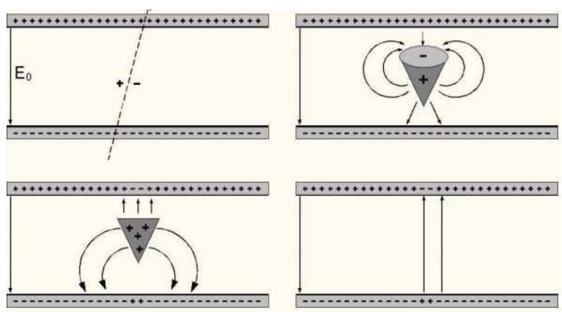


Fig2.1: Schematic of development of avalanche in an RPC

A scintillator paddle based cosmic muon telescope is used as trigger mechanism and exhibits supreme accuracy in measuring the counting rate of individual muons. Since the setup is at sea-level, the paddle helps in reducing disturbance. The underground facility will ensure that the ICAL detector faces no such problems. A paddle is made up of a scintillator tile of 1 cm in thickness, which is optically coupled to a Photo Multiplier Tube (PMT) for converting the scintillation light into an electrical signal. When the PMT is operated with a calibrated high voltage, the paddle gives a signal indicating the passage of a cosmic ray muon or any other charged particle through its scintillator tile volume. [2]

(Left) Fig2.2: Prototype of Single Gap RPC at the INO R&D lab, TIFR. (Right) Fig 2.3: Three 2m x 2m RPCs under test in the INO New R&D lab, TIFR.

3. The Multi-Gap RPC

A new type of RPC with electrically 'floating' electrodes has been developed to detect neutrinos. Unlike the single gap RPC, the gas volume in this model is divided into numerous gas gaps. The inner resistive plates are in a strong electric field and therefore take a voltage due to electrostatics. If for any reason the voltage on one plate deviates, this will cause an increase of electric field in one sub gap and a decrease in the other; the gap with the higher field will produce larger avalanches compared to the other sub-gap producing smaller avalanches. This will restore the voltage to its proper value so as to equalize the field in the two sub-gaps [3].

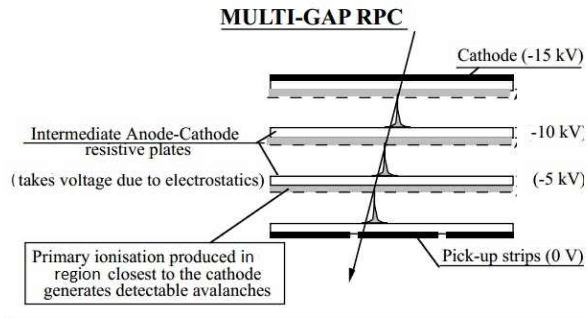


Fig3.1: Schematic showing voltage at each electrode acquired by electrostatics for a 3 gap MRPC operating at 15kV.

In any RPC the gas volume is used for producing ionizing clusters which eventually form an avalanche or a streamer. With multiple gas gaps, the internal electrodes become transparent to the avalanches in each gap and the cumulative effect of all these avalanches is induced on the external electrodes (i.e. resistive plates act as dielectric plate for these fast signals.) This leads to a better Townsend coefficient and with an ideal gas mixture the MRPC delivers a stable efficiency plateau. Most importantly, the timing resolution of a multi-gap RPC is far better in comparison to a single gap, with studies showing timing resolutions as low as 50ps (Alice, CERN).Again this improved timing resolution is attributed to the saturated avalanche growth brought about by an increased Townsend coefficient. [4] Lastly, avalanches in each gas gap are independent and large number of gaps leads to larger avalanches and hence better signals. The Multi Gap RPC was produced with the aim to improve timing resolutions and to acquire stable efficiency plateau.

3.1 Design and Fabrication of MRPC

The R&D of the MRPC was done within the institution and the detector was made mainly out of standard equipments and materials. The indigenous MRPC consists of two external glass electrodes of 2mm thickness, five 'floating' glass electrodes each of thickness 400µ, spacers (Mylar and double sided tape of approx. 250 µ thickness), edge spacers, gas nozzles and copper readout strips. The following is the process involved in the making of our MRPC.

3.1.1 Schematic of the MRPC:

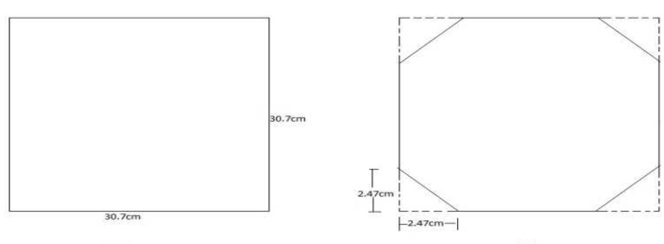


Fig 3.2: (A) The glass cut out of 30.7cm x 30.7cm required for the external electrodes (B) Chamfering of the glass 2.47 cm from each corner is done to obtain the desired shape of the external electrodes.

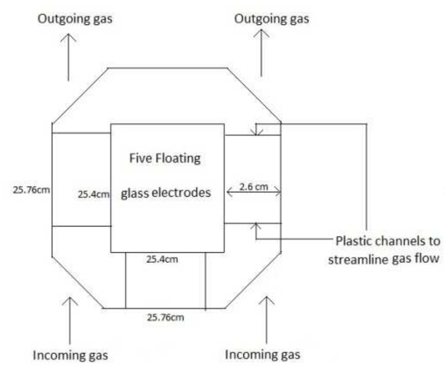


Fig3.3: Schematic showing the top view of the MRPC with plastic channels to regulate gas flow.

3.1.2 Construction of the MRPC:

1. Cutting the external glass electrodes :

Glass being highly resistive and abundantly available was chosen as the MRPC electrodes. Float glass of 2mm thickness was cut with dimensions shown in the schematic (Fig 3.2) above.

2. Coating the Graphite layer :

The cut glass was then cleaned thoroughly using Labolene (liquid soap), isopropyl alcohol and finally with distilled water. Mush tape was then cut in strips of width 2.8cm and applied on all sides of the glass electrodes to avoid paint from falling on edges as it may be counterproductive when high voltage is applied. A uniform layer of graphite using colloidal grade graphite powder (3.4 gm), Duco-lacquer (25 gm) and Duco-thinner (40 ml) was sprayed on the unexposed glass electrodes using an automobile spray gun. This graphite coating is essential as it provides the required surface resistivity to render it transparent to the electric pulses generated in the gas gap which can be easily picked up by the readout strips. Special care has to be taken to ensure uniformity of the coating.

Fig3.4: Surface Resistivity of the graphite coating was measured using indigenous jig and a multimeter.

The surface resistance was then measured using an indigenous jig (Copper plated). The jig essentially consists of two conducting bars fixed in frame so as to form a square. Provision is made to measure the resistance across these conducting bars, using a multimeter. It works on the following principle. The resistance R of a surface film of thickness t as measured between two conductors of length L and separated by width W is proportional to $L \div (W \times t)$. So for a given square of side L (which is equal to W), R is independent of L (and W) and depends only inversely on t [5]. The resistance values measured turned out to be in the range of 0.8 – 1 M $\Omega/\square$. It is important to note that the surface resistivity values drop sharply a few hours after the application of the paint, and this is primarily because of the evaporation of the thinner as time progresses.

3. Spacers

In order to make spacers we used Mylar sheet of 70 μ thickness. The Mylar sheet was thoroughly cleansed using isopropyl alcohol solution. Double sided tape of 100 μ thickness (approx.) was then pasted onto either side of the Mylar sheet. Using a standard punch, circular spacers of 4mm diameter were collected. The total thickness (Mylar + glue) was around 250 μ. Care was taken to avoid air bubble formation between Mylar sheet and tape and the spacers were applied on the glass electrodes using standard tweezers.

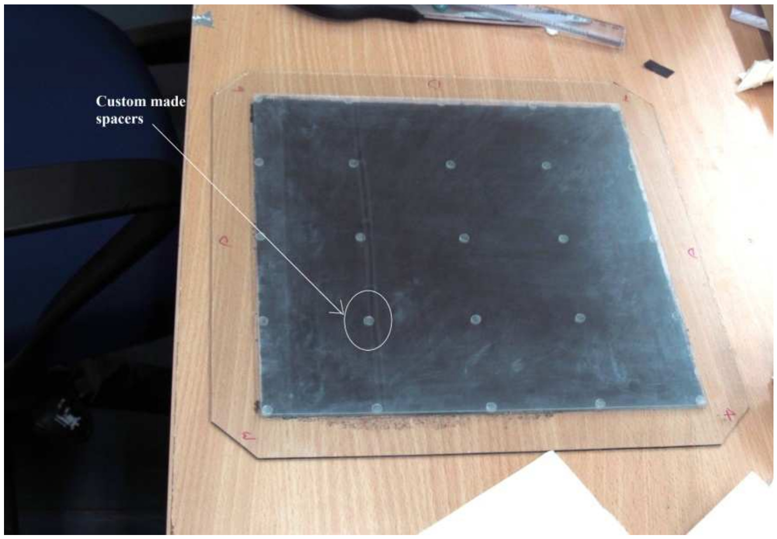


Fig3.5: The spacers applied to the external electrodes and the inner floating glass framework.

4. Floating glass electrodes :

The five floating glass electrodes, each of 400 μ, were cut into squares of side 25.4cm. The thickness of the electrodes was so decided in order to ensure the free flow of avalanches and its seamless transmission through the gas gap. The glass was then cleaned using the isopropyl alcohol solution. 25 spacers were then applied to a single glass electrode after which another glass cut-out was aligned to coincide with the first. The glue on the spacers ensured that the two glass electrodes were firmly intact. The remaining three glass electrodes were placed in a similar fashion. Finally, the entire setup – the five glass electrodes with the spacers in between them – was in turn glued onto the external glass electrodes using similar spacers.

5. Edge spacers and gas nozzles :

After the setup was allowed to rest for a few hours, the gap between the two external glass electrodes was measured using a micrometer screw gauge. The effective gas gap (subtracting the thickness of the outer glass electrodes) was in the range 3.35mm – 3.40mm. It so turned out that the edge spacers and gas nozzles used in the Single gap RPC fit perfectly in its multi-gap counterpart. In addition to this, plastic channels were also glued to ensure gas flow was uniformly spread out within the floating electrodes.

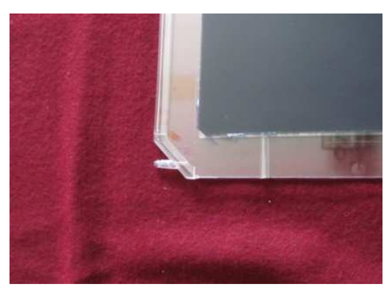
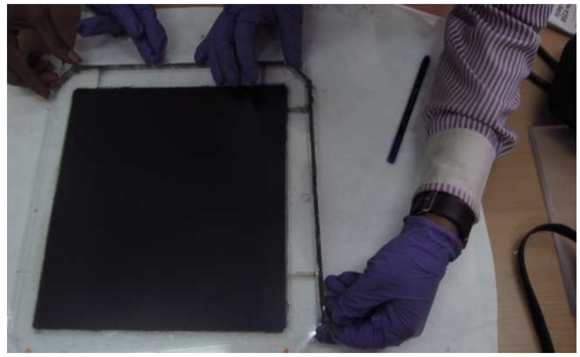


Fig 3.6: (Left) Plastic channel fitted onto an edge spacer and an edge spacer connected to a gas nozzle. Fig 3.7 (Right) The edge spacer and gas nozzle (made for the single gap RPC) fit perfectly in the gas gap of the MRPC

The edge spacers and gas nozzles were glued using a mixture of 3 M Scotch Weld or DP-190 epoxy adhesive. The glue was applied using a syringe and care was taken to ensure that the entire setup was sealed (to prevent gas leak). When the glue set on one side, the setup was rotated and the edges on the other side were glued.



(Left) Fig 3.8: MRPC, Edge spacers and gas nozzle before the application of glue. (Right) Fig3.9: Glue being applied on all edge spacers and gas nozzles.

6. Copper readout strips :

Plastic honeycomb panels laminated on one side by aluminum sheet and the other side by copper sheet was developed. The light weight and rigidity of the honeycomb made it an excellent substitute to aluminum. The pickup panels are covered with a Kapton tape. The honeycomb panel with milled copper pickup strips of width 3cm was then fixed onto the MRPC in order to induce the electric pulse signals to be transferred to the NINO board.

3.1.3 Gas mixture :

The composition of the gas is the same as in the case of single gap RPC, i.e. Isobutane (4.2%), SF_6 (0.3%) and electronegative Freon (95.5%). Isobutane, being an organic gas, helps to absorb the photons that result from recombination processes thus limiting the formation of secondary avalanches far from the primary ones. An electronegative gas may serve the purpose of limiting the amount of free charge in the gas. [6] The entire gas line plumbing is done using plastic and Tygon tubes, in order to avoid possible seepage of moisture into the gas lines. The gas mixture is constantly monitored using dedicated GUI software.

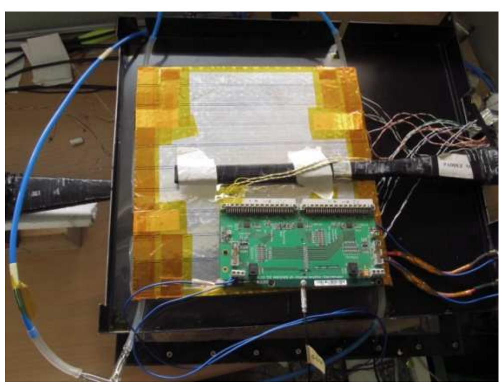


Fig 3.10: The entire setup of the MRPC including scintillator paddles, pickup panels covered with Kapton tape, gas tubes and the NINO board.

3.1.4 Data Acquisition System :

The data acquisition system used for the MRPC employs CAMAC and NIM electronic modules. The CAMAC back-end is configured with a commercial controller as its supervisor, which in turn is driven by a Linux host through an Ethernet port. The back-end system comprises of a master trigger generator, a couple of scalers, a control module and a data readout module, in addition to two TDC modules.

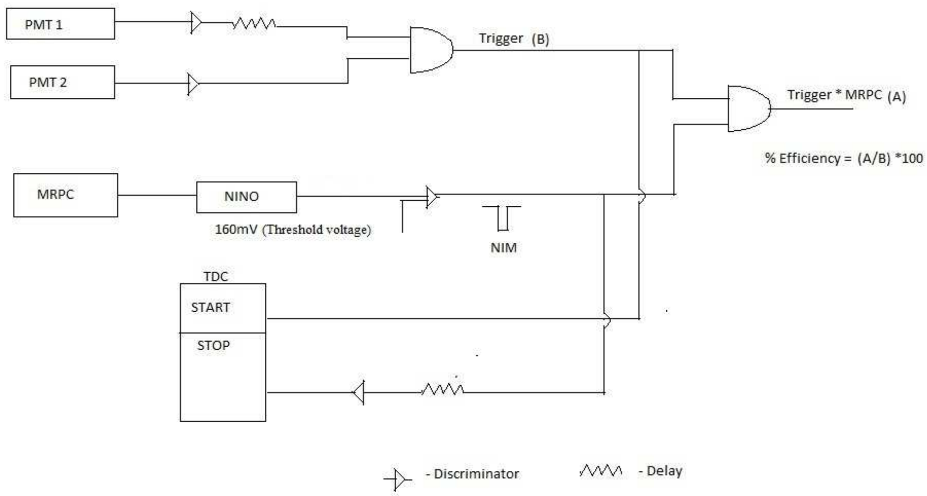


Fig3.11: Schematic showing an elementary circuit diagram and calculation of efficiency.

The signals from the scintillator paddles are converted into logic pulses using a discriminator module with threshold of about 25mV. These pulses were then used as inputs to a AND gate, the output of which was used as trigger. The logic pulse from PMT1 was deliberately delayed with respect to PMT2 so as to reduce accumulation of jitter of paddle signals. A scalar was used to maintain the trigger count. This trigger along with the logic pulse generated by passing the signals from the pickup strips of the detector through a discriminator was ANDed with a scalar module channel to maintain count. The efficiency can then be calculated as the ratio of its coincidences with the triggers and the triggers themselves.

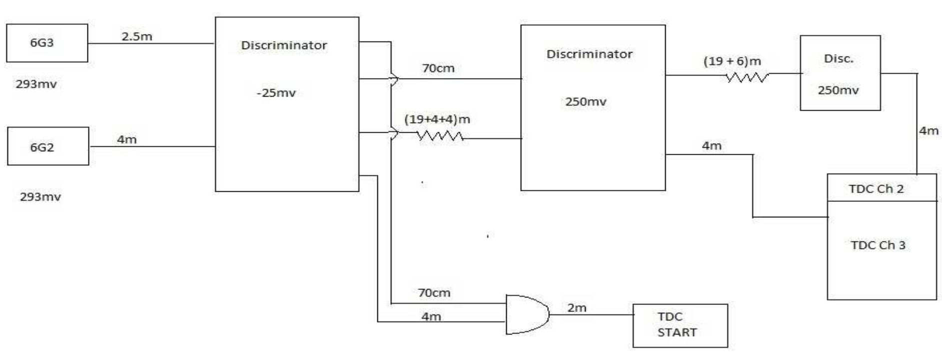


Fig3.12: Circuit Diagram of the DAQ. (From detector, paddles to TDC)

The paddle signals (muon telescope) were also used as START for the TDC module while the MRPC signals served as STOP for the TDC (ch2 and ch3). The entire setup was placed in a NIM and a CAMAC crate. The telescope monitor system and CAMAC crates were constantly observed by PC hosts in which dedicated software displayed real-time data from the setup. While the telescope monitor system collects displays and stores all scaler counters' data at equal chosen time intervals continuously, the RPC system waits for the cosmic ray muon trigger, to initiate data acquisition for that event. The data once collected was analyzed using programs such as ROOT which interprets the results using standard physics analysis. Aside from this, the high voltage and noise rate were also monitored to get a comprehensive view of proceedings.

4. Preliminary Results and Analysis

We started our data collection and analyzing by studying some of the basic operating characteristics of the detector such as voltage–current relationship, individual counting (or noise) rates of the RPC, efficiency of strip, timing resolution and so on.

4.1 I-V Characteristics:

The voltage is ramped up to check for current leakage. Given below (Fig4.1) is the relationship between the applied high voltage and the subsequent current measured. At lower voltages the primary ionization cluster formations do not lead to avalanches. As the voltage increases there is an increased gas gain and the current becomes substantial. The current is determined mainly by the resistance of the spacers, the gas composition and the voltage applied.

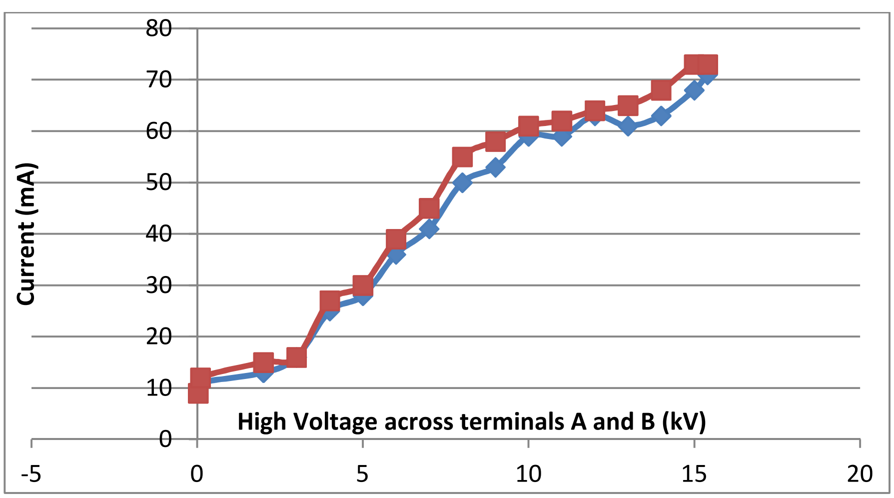


Fig4.1: I-V characteristics of the MRPC detector.

4.2 Noise Rate:

Noise Rate of an RPC is the total counting rate of all its signals above a particular discriminator threshold. These signals are produced by cosmic ray charged particles which are often a result of stray radioactivity surrounding the detector. The noise rate is measured per unit area of a single strip as the scintillator paddles can coincide with only one strip. These values can be averaged over a reasonable length of time and the noise rate of the entire MRPC can be found. Noise rate is an important characteristic as it reflects the long term stability of the detector. A sharp or sudden increase in the noise rate might result in a reduction of the voltage across the electrodes thus affecting the gas gain and the efficiency of the detector. Fig 4.2 shows a fairly linear relationship between voltage and noise rate. As expected, when the voltage increases the noise associated with lower energy particles also become detectable.

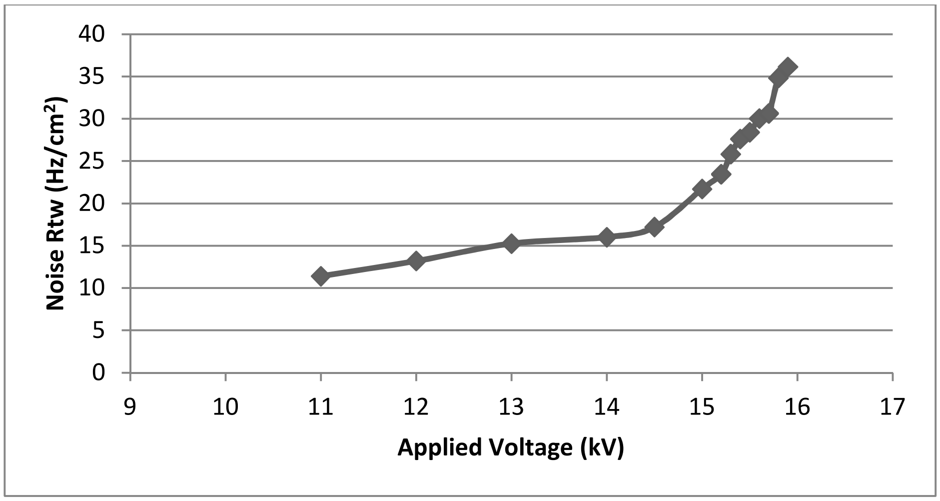


Fig4.2: Noise rate as a function of applied voltage of the MRPC.

4.3 Efficiency:

Fig 4.3 shows the percentage efficiency of a readout strip as a function of the applied high voltage. Efficiency is measured as the number of muons crossing the detector in comparison to the trigger generated by the paddles. Using the same gas mixture and increasing voltage we get efficiency of up to 94%. However a stable efficiency plateau might require higher voltage or a slight alteration in the gas composition.

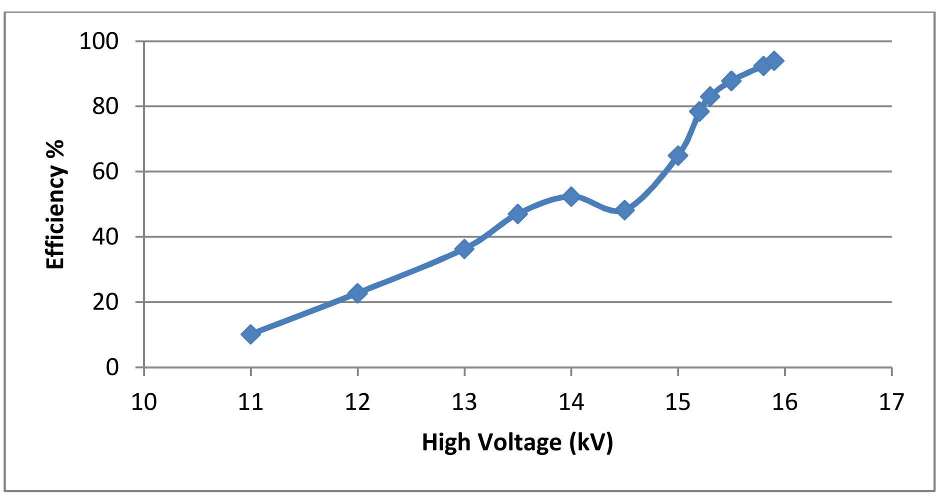


Fig 4.3: Percentage efficiency as a function of the high voltage applied to the detector.

4.4 Timing resolution:

The timing is measured through the spread in its temporal response to a charged particle passing through its gas volume, with better time response giving smaller time spread leading to a more accurate time measurement.[6] Therefore a better time resolution will yield a narrower curve in the graph. In Fig 4.4 the timing resolution of the MRPC was found to be 1.26ns. However this includes the time response of the scintillator paddles. In the future, by replacing the paddles with MRPCs it is possible to improve the timing resolution by a great extent as it will become easier to discriminate between responses from trigger and detector. The following histograms were plotted using ROOT software.

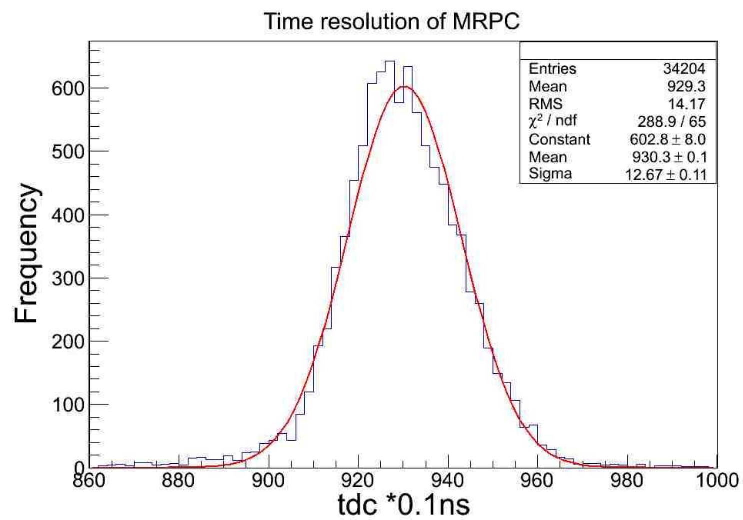


Fig 4.4: Showing the timing resolution of the MRPC to be around 1.26 ns.

5. Conclusion

The preliminary results from the MRPC are encouraging. The timing resolution can be further improved by replacing the scintillator paddles with MRPCs. At the same time, gas composition can also be altered and an optimum mixture can be found to increase the gas gain and ensure a stable efficiency plateau for the MRPC. If the desired timing resolution is obtained, MRPCs can be used as a feasible alternative to scintillator paddles in the ICAL detector for the INO experiment. In addition MRPCs can also be used in tomography studies and in the medical field.

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