Time of Flight (TOF) - Positron Emission Tomography (PET) imaging using 5-gap Glass Multi-gap Resistive Plate Chambers (MRPCs)

A
Thesis
Submitted for the Award
Of the Degree of

Masters of Physics
By
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Certificate

This is to certify that the thesis entitled '**Time of Flight (TOF) – Positron Emission Tomography (PET) imaging using 5-gap Glass Multigap Resisitive Plate Chambers (MRPCs)**' submitted by **Ms. Shaifali Mehta** (Roll No. 301404024) student of M.Sc. Physics, Thapar University, Patiala, was carried out by her under the supervision and guidance of **Dr. Tapan K Nayak** and **Ms. Loveleen Kaur Brar**. She has not submitted this material for credit towards any other degree at Thapar University, Patiala or any other university.

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CERTIFICATE

This is to certify that the work embodied in the thesis entitled "**Time of Flight (TOF) Positron Emission Tomography (PET) imaging using 5 gap glass Multigap Resisitive Plate Chamber (MRPC)**" has been successfully carried out by Ms. Shaifali Mehta in Experimental High Energy Physics & Application (EHEP & A) group at **Variable Energy Cyclotron Centre, Kolkata, India.** She carried out the work independently under my supervision. I certify that the record of this thesis is original.

17/6/2016

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Declaration

I hereby declare that thesis entitled "**Time Of Flight (TOF) - Positron Emission Tomography (PET) imaging using 5-gap Glass Multi-gap Resistive Plate Chambers (MRPCs)**" is the original work carried out by me under the supervision of **Ms. Loveleen Kaur Brar**. The matter embodied in this thesis has not been submitted anywhere else for the award of any degree.

Shaifali Mehta

(301404024)

M.Sc. (Physics)

Dedicated to my parents with love

And who believe in me and my dreams

Dedicated to my parents with love

And who believe in me and my dreams

Abstract

Time of Flight (TOF) technique is used in Positron Emission Tomography (PET) imaging worldwide. PET imaging technique, is based on two back to back photons created by the annihilation of positron (e+) (generated by FDG (radio-tracer) inside the patient's blood stream) with electron. The scintillator based detectors currently in use are very costly, so to minimise the cost, we are developing a different type of detector called Multi-gap Resistive Plate Chamber (MRPCs). MRPCs are very low cost detectors and can be fabricated over large areas having time resolution of ~10 ps. Hence they can be a suitable replacement to scintillators for PET imaging.

In the current work, we have fabricated and characterised two identical (18 cm x 18 cm) 5-gap glass based MRPCs. The fabricated MRPCs were kept one over the other separated by a distance of 40cm. In our experiment, the source (Na-22) position was shifted physically by ~12 cm and the data from MRPCs nearly matched with the same. This proves the suitability of the fabricated MRPCs for TOF measurements.

Acknowledgements

With immense pleasure, I am really thankful to my supervisor Dr. Tapan K Nayak for allowing me to work in VECC and his constant and invaluable motivation. He is a kind of mentor who everyone wish to have and I consider myself lucky enough to get the opportunity to work with him. Without his dedicated supervision, it would not have been possible for me to complete my thesis work.

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Contents

Chapter 1

INTRODUCTION TO DETECTORS

In experimental high energy physics, particle detectors are used to trace or spot the presence of incoming particles. Particle detectors which are used for measuring the radiations are called radiation detectors. The origin of particle detectors takes us back to the discovery of X-Rays and Radioactivity discovered in late 1895 by W.C.Roentgen when he was working with cathode ray tubes. The existence of modern gaseous detectors arrived from the works of Ernest Rutherford where he performed his famous Gold Foil Experiment which led to the discovery of an alpha particle.

1.1 Scintillation Detector

Scintillation detector was of the first radiation detector discovered. Scintillation is the property of luminescence and the materials which exhibit luminescence are known as scintillators. When incoming particle strikes luminescent material, its energy is absorbed and re-emitted in the form of light. The scintillation detector is one amongst those detectors which are widely used for particle detection in nuclear and high energy physics.

There are different types of scintillators, say, gaseous, liquid, solid, organic, or inorganic. Scintillation based detectors comprises a scintillator material coupled with a photo detector. A photo detector converts the light from the scintillator into electrical signals. One of the most common photodetectors are the photomultiplier tubes composed of photo cathodes (figure 1.1), followed by many dynodes. The light photon when strikes the photocathode emitting photoelectron is focused onto the first dynode. This produces electrons that are multiplied at the each dynode down the chain, thus producing an amplified signal which is then collected at the anode and passed out to the measurement circuits.

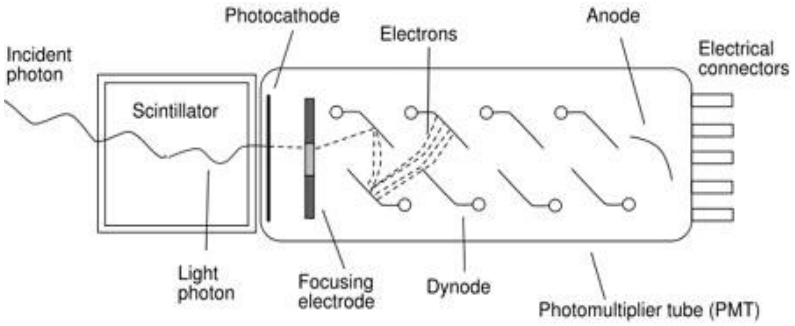


Figure 1.1 Schematic diagram of a scintillation detector [1]

1.2 Gaseous Ionization Detector

In 1928, a detector invented by Geiger and Muller was mainly directed towards the collection of ionisation electrons and ions produced when the radiations were passed through. It consists of metal tube or cylinder of radius 'b' with a thin metallic wire of radius 'a' in its centre, filled with a noble gas.

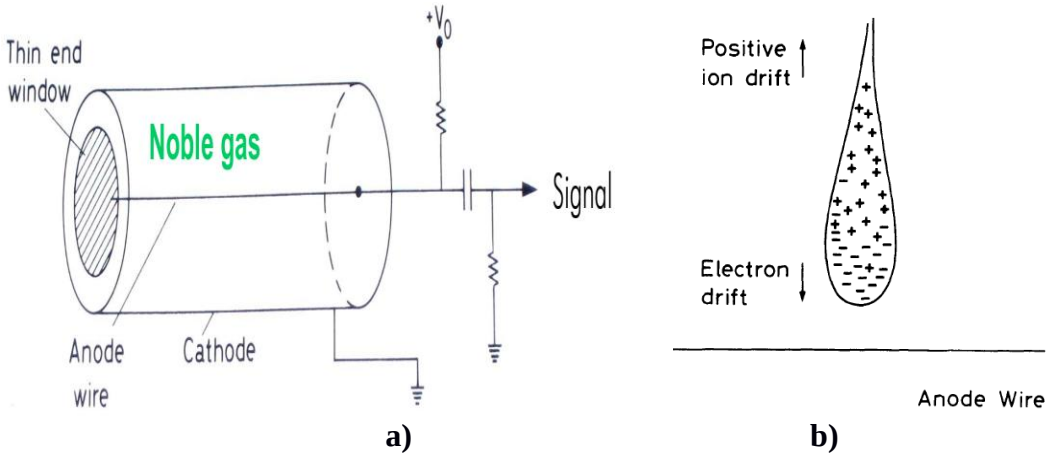


Fig 1.2: a) Basic construction of Geiger tube [2] b) Development of an electron avalanche [3]

For an incoming particle penetrating the detector, a large number of electrons and an equal number of positive ions (proportional to the energy deposited in the counter) are formed due to ionization of gas. Under the influence of the uniform electric field, electrons accelerate towards the anode and the ions drifts towards the cathode where they are collected. On applying high electric field, primary ionization electrons gain sufficient amount of energy and cause further ionizations. This multiplication results in the formation of an avalanche. The avalanche takes the form of a liquid-drop with the electrons grouped near the head (because of the greater mobility of the electrons) and the slower ions trailing behind (Figure 1.2 (b)).

Figure 1.3 gives the graph for variation of number of ions collected versus the applied voltage

difference for a Geiger Muller tube.

Based on this principle in the first half of the century, three basic types of gas detectors were developed: - **The Ionization chamber**, **the proportional counter** and **the Geiger-Muller counter**. Figure 1.3 gives the regions of operations for different detectors.

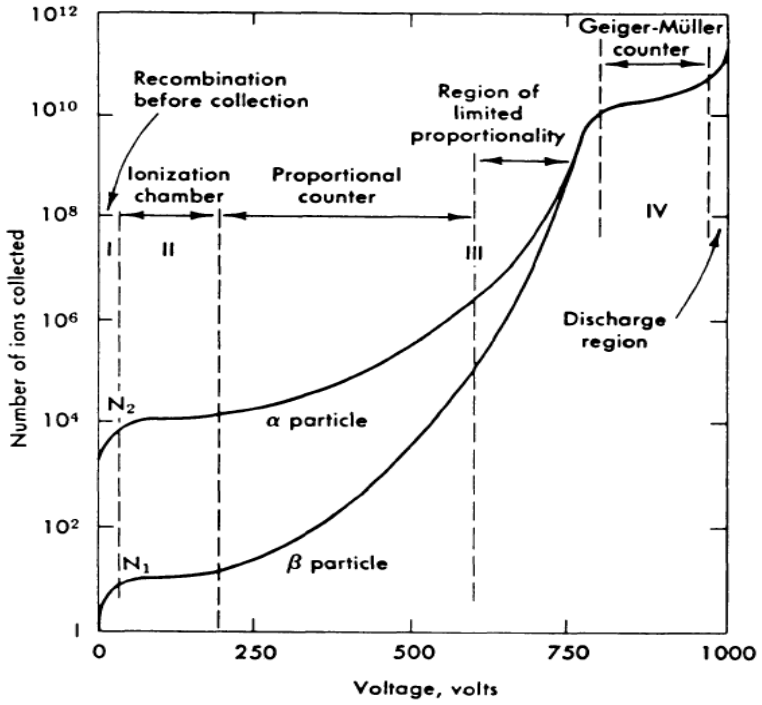


Figure 1.3: Number of ions collected versus the applied the voltage difference in a Proportional tube. [2]

1.2.1 Ionization Chamber

The process by which atoms or molecules gains charge (can be positive or negative) depending upon the gain or loss of electrons to form ions is known as the ionization. Ionization chambers have a relatively low voltage of a few 100 V between anode and cathode which results in the collection of charges produced in initial ionization event. The output signal produced by these signals is very weak. To get strong output signals, increase the respective energy and intensity of the radiation. Since ionization chambers have no "Dead Time", they are generally used for measuring gamma ray exposure.

1.2.2 Proportional Counter

Proportional Counters are operated at a slightly higher voltage between anode and cathode where the discrete avalanches are generated and charge amplifies exponentially. At this voltage, the number of particles liberated by secondary interactions is proportional to the number of ions produced by the passing ionizing particle. Such type of gas ionization detectors are called proportional counters. The advantage of proportional counter is that it can discriminate between alpha and beta particles.

1.2.3 Geiger-Müller or Breakdown Counter

If the voltage is increased further, the Geiger -Müller regime is reached where a series of secondary avalanches spreads along the entire length of anode wire. These secondary avalanches are triggered due to UV photons emitted by de-exciting molecules formed in the process of avalanche multiplication in other parts of the counter. Eventually, the output current becomes completely saturated regardless of the energy of the initial event. The reason being: excessive avalanche formation and space charge around the anode wire reduces the electric field to a point where no more avalanche formation takes place. The voltage drop over the external resistor in series also contributes in stopping the avalanche multiplication process. In order to absorb the photons and stop the discharge, a quenching gas must be present in the medium. Large output signal from tube requiring minimal electronic processing is an advantage of this regime. The drawback is that the counter has a very large dead time of 100 μs and low count rate capability.

1.2.4 Wire and Drift Chambers

In late 1960's, gaseous detectors like wire and drift chambers [4] came into existence. But these detectors introduced the problem of time jitter, limiting the time resolution of wire based detector to a few nanoseconds. Time jitter is the fluctuations in the time caused by noise and these random fluctuations will not allow any two identical signals to trigger at the same time.

1.2.5 Keuffel Spark Counter

Since gaseous detectors were having a good spatial resolution but to overcome the problem of

time jitter and to improve the time resolution, a strong uniform electric field needs to be applied. In 1948, Keuffel Spark Counter was the first gas detector to use uniform electric field with parallel metal plate geometry. It offered a time resolution of around 1ns which was far better than any of Geiger Muller counter. Keuffel Spark Counter consists of two planar metal electrodes with a high voltage applied to them and a gas mixture filled between gaps. When a charged particle passes through this gap, it leaves a trail of free charge carriers produced by primary ionization of the gas particles in the gap, which trigger avalanches of charge carriers in the electric field. At a certain size, the avalanches transform into streamers, where photons produced by the recombination process, contribute to the spread of free charge carriers. At a later stage, a conducting plasma filament connecting the two electrodes is formed, through which the electrodes are discharged, and a spark is created leading to large signals that needs no further amplification, thus avoiding electronic time jitter. Due to the spark produced in the gas, a switching-of circuit is needed to prevent the metal electrodes from being short-circuited. This leads to a long dead time (~1 s), which poses limits on the maximum detection rate it could sustain. In addition, it worked with low-pressure gas and had a very short operating span. Note that the standard spark chamber has an area of the order of a few cm^2 only because with the increase in the area, the discharge energy in a spark increases to an extent that it can damage the electrode surface.

1.2.6 Pestov Spark Counter

Pestov spark counter was introduced in 1971 [5], with metal cathode, semi-conducting glass anode as electrodes and special gas mixtures for photon absorption. The resistivity of the electrodes is ~10^9 Ω-cm which limits the discharge to local area near the primary avalanche. Since the drop in high voltage is temporary, the remaining counter area is still sensitive to particles. The energy in the sparks is much smaller than in the case of metallic electrodes and larger electrode surfaces can be used. Moreover, if organic gases with high ultra violet absorption capability are used then charge diffusion in the gas will be prevented and the area of the detector which undergoes voltage drop is localised around the primary ionisation region. The purpose of using resistive electrodes is that high voltage switching of circuits is no longer necessary and consequently a higher detection rate can be achieved. Time resolution down to 25 ps can be achieved using the Pestov Spark Counter with a 0.1mm gap. However, the very thin gap (0.1mm) combined with the high values of the electric field (500

kV/cm) demand a very good surface smoothness of the electrodes. To account for good detection efficiency, the detector has to be operated at a large overpressure of 12 bar. Figure 1.4 shows a simple schematic of pestov counter.

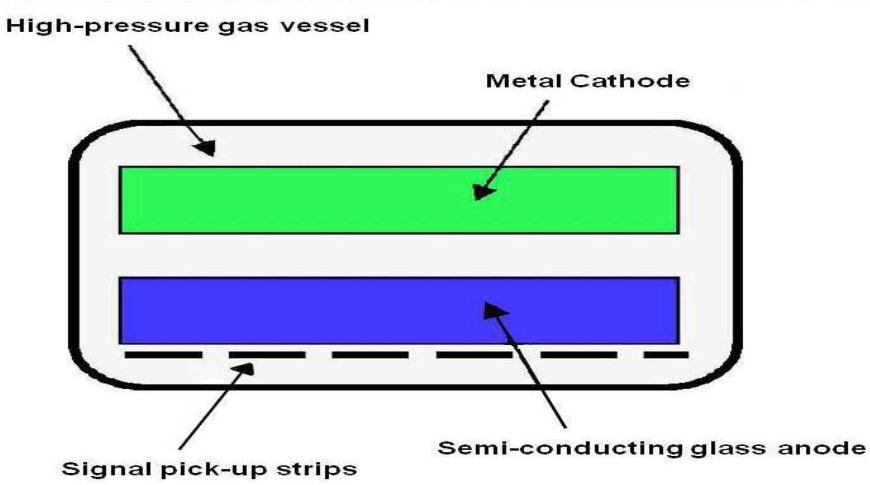


Figure 1.4: Schematic diagram of Pestov Counter [6]

1.2.7 Parallel Plate Avalanche Chamber (PPAC)

Parallel Plate Avalanche Chamber is a single gap gaseous detector operated in avalanche mode and is very similar to the Spark Counter. It normally consists of two planar metal electrodes, or metalized ceramic or plastic, with a gap of 0.5 to 2 mm by precise spacers. Its advantages include a fast response and an increased rate capability of up to 10 MHz / cm^2. The time resolution is 100 to 250 ps. Depending on the gas filling, a gain of 103 to 104 can be reached with a very low discharge probability of 10-5 for minimum ionizing particles. The PPAC signals are small (about 100 fC on an average) which gives a low signal-to-noise ratio. For good detection efficiency, low-noise electronics is used which collides with the fast rise time needed for timing purposes. Formation of streamers and discharges are unwanted side effects in this type of detector. The possibility of using this technology for large scale applications is questionable.

Chapter 2

MULTI-GAP RESISTIVE PLATE CHAMBERS (MRPCs)

Multi-gap Resistive Plate Chambers (MRPCs) are the advanced state of Resistive Plate Chambers (RPCs). RPCs are the most affordable parallel plate gas detectors working on the principle of gaseous ionization. These detectors are extensively used in High Energy Physics and Astroparticle experiments [4]. The main feature of RPCs is that they are robust, easy to fabricate, can be fabricated in any size and have simple electronics associated. RPC utilises a constant and high uniform electric field (~50-100 kV / cm) produced between highly resistive electrodes (10^{10} -10^{12} Ω-cm). A single-gap configuration provides time resolutions down to ~1 ns and position resolution of a few micrometers, whereas a multi-gap configuration can give time resolutions down to 20 ps [8]. This makes RPCs well-suited for TOF (Time of Flight) applications, medical imaging and triggering purposes. Large Hadron Collider (LHC) at CERN uses RPC-based muon triggering systems for ATLAS [23], CMS[22], ALICE-TOF.

Resistive Plate Chambers (RPCs) were first introduced in 1981 by R.Santonico and R. Cardarelli [9]. RPCs consist of two parallel plate electrodes which are made of highly resistive material (~ 10^{9} – 10^{12} Ω-cm) say, glass, or bakelite. A constant gas gap between the electrodes is maintained using the spacers having higher resistivity than electrodes. Between these highly resistive electrodes, mixture of gases is sandwiched. These electrodes are coated with graphite paint for uniform electric field. When the charged particle passes through the detector, it ionizes the gas, ions and electrons move towards the respective electrodes. To read out the signals due to ionization, a signal electrode (separated from graphite layer by a mylar film) is placed on the outer electrode. They are placed along the whole length of the electrode to pick up the signal. In order to locate the particle's location at the time of primary ionization, the signal electrode is applied in the form of strips and the strips are placed perpendicular to each other on the opposite sides. For the signal electrode normally copper strips (thickness ~ 0.5 cm) are used.

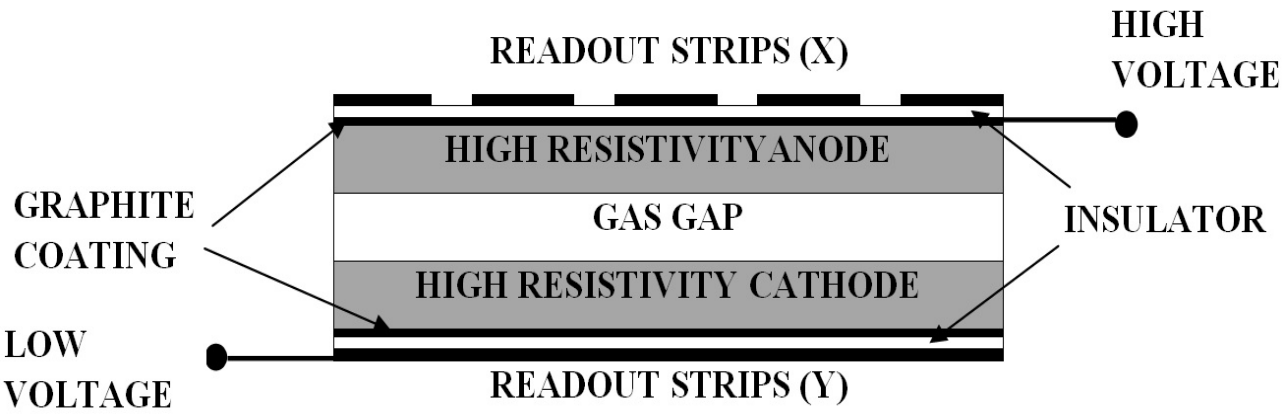


Figure 2.1: Schematic of Resistive Plate Chamber [10]

2.1 Working principle of RPC

The main task of a detector is to detect the signals and to give the information regarding the same. The basic principle upon of any gas detector is: Ionization of gas. When the charged particle passes through the gas volume it gives rise to the formation of electron-ion pairs. Since the drift velocity of electrons is very high, on applying the high electric field, electrons drift at a faster pace and produce further ionisations. This leads to multiple ionisations which take the shape of an avalanche. These electrons when de-excited emit photons, which leads the formation of secondary avalanches. Time resolution of RPCs is much better than that of spark counter or proportional tubes because RPCs uses uniform and constant field. For a single gap RPC, typical time resolution is ~1-2 ns, which can be further increased to ~50 ps either by reducing the gas gap between the electrodes or by using the multi-gap configuration. Multi-gap configuration will be further explained in detail in section 2.3.

When the chamber gain is high enough, the local electric field produced by the avalanche influences the electric field within the gap due to space charge effect. In the regions above and below the avalanche (with electric field E_1 and E_3 respectively), the net field is more than the applied electric field (E_0) (because the both fields are in the same direction). But in the region where the avalanche is present (region of highest electron density), the local induced field (E_2) and applied field (E_0) cancel each other [6] [10] (figure 2.2).

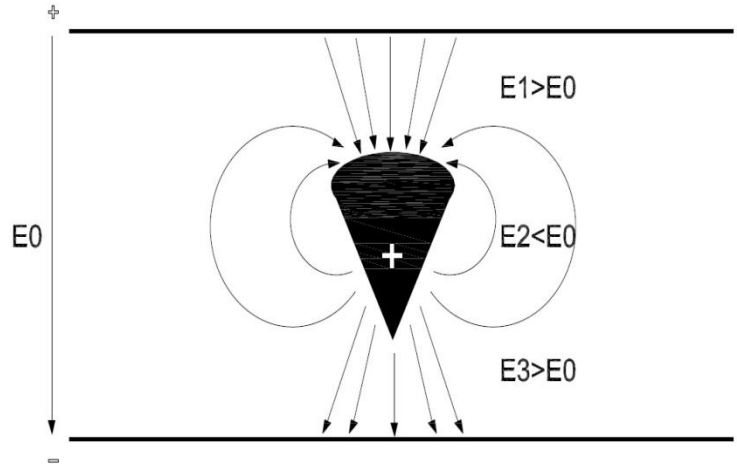


Figure 2.2: Schematic of an avalanche and the electric field variations caused by the avalanche charge carriers inside the RPC [6]

2.2 Classification of RPCs

RPCs are classified into multiple categories:

2.2.1 Based upon the application

Based upon the application RPCs are classified in two types:

1. Trigger RPCs
2. Timing RPCs

2.2.1.1 Trigger RPCs

In some experiments, particle strike needs to trigger further circuits. RPCs used for this purpose are referred to as Trigger RPCs. They are used in various high energy physics experiments for triggering the Minimum Ionising Particles (MIPs) like muon. RPC with gas gap of 2 mm be it single gap or double gap, operated in avalanche mode or streamer mode gives efficiency ~98% with a time resolution ~1-1.5 ns and such RPCs are used as the Trigger RPCs [11].

2.2.1.2 Timing RPCs

RPCs which give timing information of the particle striking the detector is referred to as the timing RPCs. Timing RPCs are mostly operated in avalanche mode to get better time resolution of ~50 ps with an electric field of ~100 kV/cm. These RPCs provides an efficiency

of ~99%. The time resolution of timing RPC is better than trigger RPC. RPCs with the gas gap of 0.2 – 0.3 mm wide are mostly used in multi-gap configurations for the Time-of-Flight (TOF) measurements.

2.2.2 Based upon the design

The combination of different kinds of resistive electrodes and their materials, types of pick up panels used, types of spacers used, RPCs can be classified in different categories on the basis of their design:

2.2.2.1 Single-gap RPC

When the original RPC was fabricated in 1981, it was a single gap RPC with high resistive electrodes of bakelite. Later on according to the need, glass RPCs were fabricated which showed better resistivity and are in trend nowadays. The inherent advantage of this design is that high voltage capacitors are absent and thus the high voltage insulation of the strip is not required.

Time resolution of ~1-1.5 ns is obtained in a standard 2 mm gap RPCs in either of the operating modes [6]. To obtain such results discriminators (for e.g. Leading Edge Discriminator (LED)) are used. In the conventional single gap RPC to maintain a constant gas-gap, gas mixture of Argon, iso-butane, tetra-fluoro-ethane (R134a) is used and is operated at streamer mode.

2.2.2.2 Double gap RPCs

Double-gap design is almost the same as the signal-gap but with more number of elements involved in it. The main purpose to introduce the Double-gap design was to improve the detection efficiency of the detector while operating it in the avalanche mode [2]. A schematic of double-gap RPC is shown in figure 2.3 below.

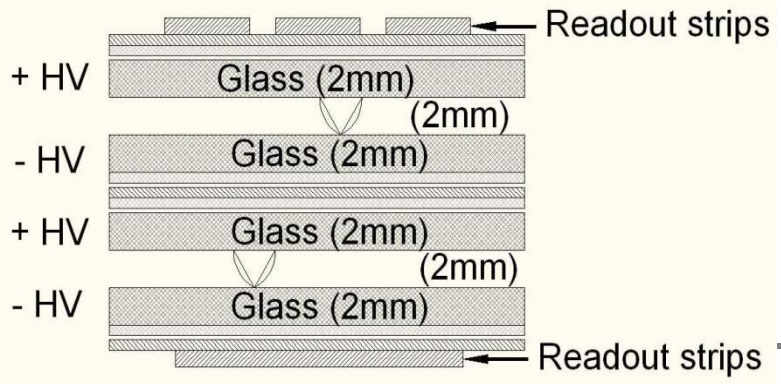


Figure 2.3 Schematic showing Double-gap RPC [6]

2.2.2.3 Multi-gap RPCs

Multi-gap Resistive Plate Chambers (MRPCs) are nothing but the extended version of RPCs where the single gap of RPC is divided into many small sub-gaps to improve the time resolution of the detector. This is done by inserting highly resistive electrodes (~10^{9}-10^{12} Ω-cm) floating within the gas gap between the two outer electrodes. High voltage is applied on the two outer electrodes. When the charged particle passes through the gas gap, formation of avalanche takes place in many of the gaps. The signals induced on the pick-up strips are the sum of the individual avalanche signal in any of the gas gaps. In case of MRPCs time jitter is expected to be less because of the small gaps.

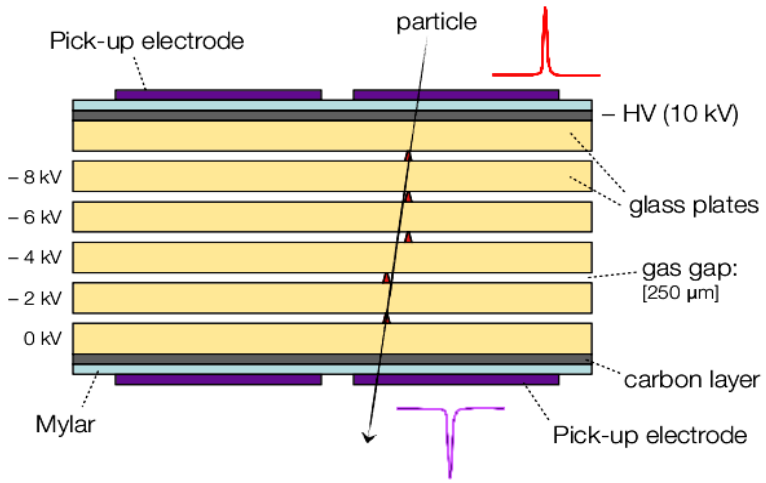


Figure 2.3: Schematic of Multi-gap RPCs (MRPCs) [17]

2.2.2.4 Hybrid RPCs

Hybrid RPCs are made of resistive and metallic electrodes. A schematic of hybrid RPC is shown in figure 2.4 below. The electrodes connected to high voltage are metallic where as the floating electrodes are made of highly resistive material. The cathodes are connected to the negative high voltage and anodes are connected together, kept at ground potential. These detectors are simple and easy to construct and have a very good time resolution <50 ps and detection efficiency >95%. These types of RPCs can also be used for ToF-PET imaging [6] [11]. But these RPCs give very poor timing resolution because of conducting electrodes. That's why Multi-gap RPCs are preferred over Hybrid RPCs for their excellent timing

resolution because of the presence of resistive plates.

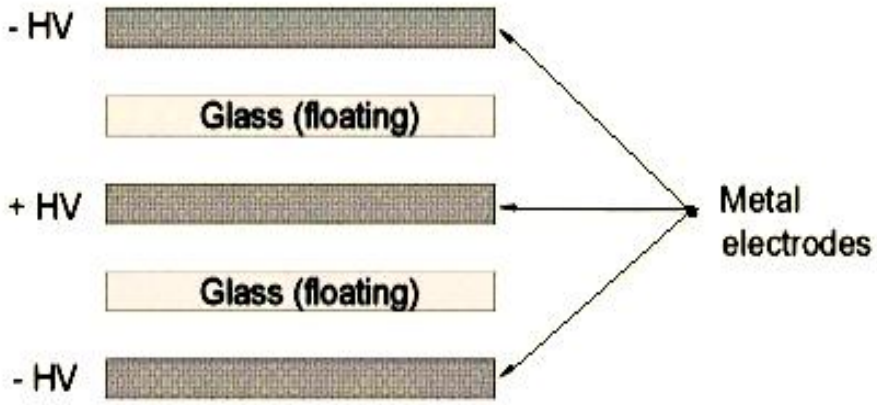


Figure2.4: Schematic of Hybrid MRPC [12]

2.3 Multi-gap Resistive Plate Chambers (MRPCs)

The concept of Multi-gap Resistive Plate Chambers (MRPCs) came into picture for improving time resolution of the detector. In RPCs, to get a detectable signal the avalanche should grow rapidly. This can be done by increasing the electric field but then there is a possibility that the detector would not work properly since many avalanches will combine to form a streamer. So avalanche multiplication to this huge extent needs to be stopped. The best possible solution is the addition of highly resistive electrodes in the gas-gap.

The single gap in RPC can be divided into many sub-gaps. The increase in the number of gas-gaps leads to high detection efficiency and reduces time jitter. This will minimise the growth of the avalanche since by the time electrons reach the intermediary plate, it induces the charge on the pick-up strip. All the resistive electrodes are kept floating using the polycarbonate spacers to maintain the gas-gap. The voltage is applied only to the external electrodes.

When the charge particle, say, cosmic muon will pass through the detector, it will form an avalanche. The avalanches formed will make the electron to strike the anode and positive ions to strike the cathode surface. On applying the same electric field on the electrodes, gas gap between the two intermediate plates is the same, the rate of avalanche formation through each gap will be same. This indicates that on an average the rate of flow of electrons on side of the resistive electrodes is balanced by the flow of positive ions on the other side. So, the net charge that flows through the plate will be zero [13].

2.4 Modes of Operation

Depending on the application, Multi-gap Resistive Plate Chambers (MRPCs) can be operated in two modes: 1. Avalanche Mode 2. Streamer Mode. It depends upon the purpose for which the detector is being fabricated that which mode will be best suited. In avalanche mode the release of primary charge by the incoming ionising radiation is followed by generation of Townsend avalanche where as in streamer mode the avalanche is followed by a spark or "streamer".

2.4.1 Avalanche Mode of operation:

In this mode, formation of an avalanche takes place when the ions or electrons created due to the primary ionization create more number of ions or electrons by the secondary ionizations. (For an avalanche mode, the operating voltage is <10 kV).

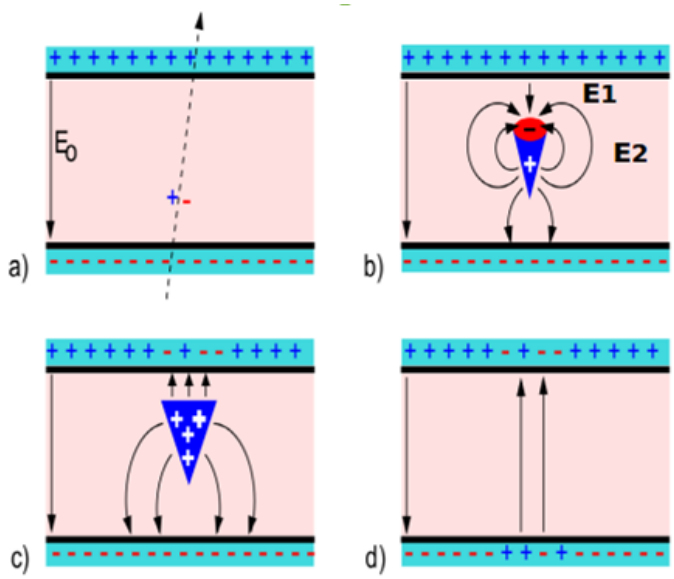


Figure 2.5: Schematic showing avalanche mode of RPCs [14]

Figure 2.5 above shows the schematic of the avalanche mode in RPC (E_0 is the external electric field applied). When the charged particle passes through the detector, multiple ionizations takes place leading to formation of multiple electron-ion pairs. To prevent the electrons and ions from recombining, high electric field E_0 is applied externally (going from cathode to anode). For large enough electric field electron-ions will form an avalanche. These electrons and ions will generate an internal electric field, E_2 (this field is shown through the

electric field lines). Since the direction of this field is opposite therefore $E_2 < E_0$ and E_1 is the field induced. $E_1 > E_0$ since the field induced is in the direction of the applied electric field E_0.

In avalanche mode,

$$E_2<E_0 \quad (2.4)$$

$$E_1>E_0 \quad (2.5)$$

The pulses in this mode are of the order of mili-volt and to amplify the signals pre-amplifier is required.

2.4.2 Streamer Mode of operation

Streamer mode is the advancement in the avalanche mode. For the streamer mode operating voltage is very high. In this mode, there are large numbers of ionizations produced. Electrons are collected towards anode and their ions are collected at the cathode. There will be collection of electrons and ions near the electrode plates and since the gap is small (~2mm), this charge collection near the electrodes will cause a short circuit as high electric field is applied. Short circuit will cause the current to flow and will produce a spark as shown in figure 2.7.

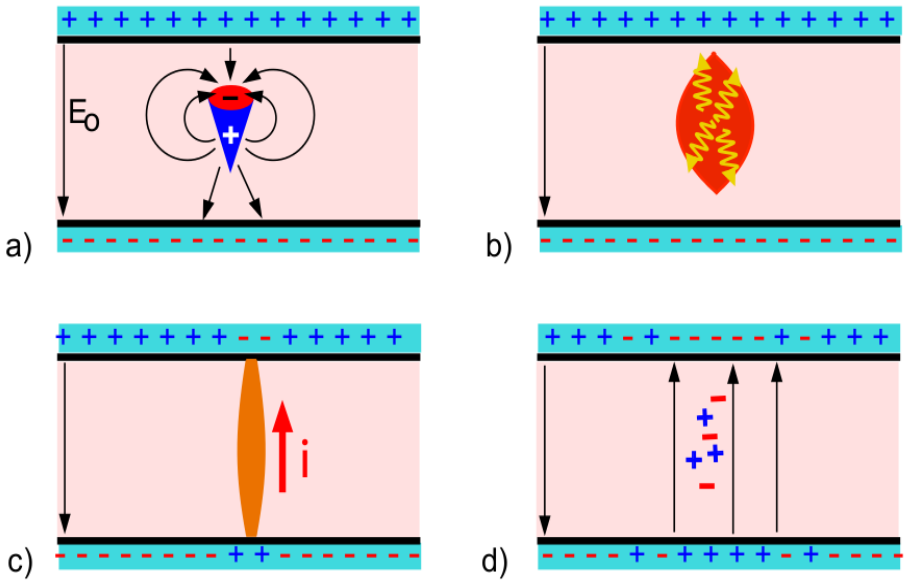


Figure 2.6: Schematic of Streamer mode of RPCs [14]

The pulse produced in streamer mode would be of the order of some 100 mV. Since the pulse amplitude is large (~200 mV) so no pre-amplifier is required in this mode which reduces the front-end electronics.

2.4.3 Raether limit

In an experiment the avalanche mode and streamer mode are differentiated on the basis of Raether limit.

If at some particular point, there are "n" number of electrons inside the gas-gap the rise in the number of electrons during the unit path length is given by townsend equation:

$$dn = n \alpha dx \quad (2.1)$$

where,

α = first townsend coefficient

The total number of electrons created in path x is given by the equation

$$n = n_0 e^{\alpha x} \quad (2.2)$$

where,

n_0 = Total number of primary electrons

If n_0 be the total number of electrons then multiplication factor given by

$$M=n/ n_0 = e^{\alpha x} \quad (2.3)$$

where;

n = Total number of the electron reaching the anode

n_0 = Total number of primary electron

α = First Townsend coefficient

x = the distance between the anode and the point where primary ionisation created.

The mode of operation of RPCs is decided by the multiplication factor, M. If the multiplication factor M << 10^8, the operating mode will be the avalanche mode and if M >> 10^8, the operating mode w1ill be the streamer mode. This is known as the **Raether limit** [2].

2.4.4 Avalanche mode versus streamer mode for RPCs

	Avalanche Mode	Streamer Mode
1.	Gas mixture used is Freon:Isobutane:SF6 in the ratio 95:4.5:0.5.	Gas mixture used is Argon:Freon:Isobutane in the ratio 55:40:05.
2.	Small pulse amplitude (~5mV), sophisticated front-end electronics is required.	large pulse amplitude (~200mV), no amplifier is required.
3.	Reduces the aging of RPCs.	Increases aging in RPCs.
4.	Operating voltage is ~15 kV.	Operating voltage is ~9 kV.
5.	MRPCs are generally operated in this mode.	RPCs are generally operated in this mode.

2.5 Gas composition and Gas system

For the proper functioning of the detector, it is necessary to have the proper gas flow through the detector for the ionisations to take place. Usually noble gases are being used for the minimum working voltage, since noble gases are highly unreactive and have low ionization energy. Argon or Freon is usually preferred for this task because of their high specific ionisation. Freon is preferred (134A is its eco-friendly substitute) because of its low ionisation energy and highly electronegative nature allows it to acts as an ionizer as well as electron quencher.

The ionisations produced in the avalanche mode due to the presence of Freon causes the atoms to excite and they de-excite emitting high energy photons. These emitted photons further help in the ionisation of the gas and causes cascading avalanches, which are often undesirable. To overcome this problem, polyatomic gases say, isobutane are added to the mixture. Isobutane plays the role of photon quencher as the molecules of isobutane absorbs the photons and the extra energy gained is then dissipated, where the kinetic energy of the two molecules in the final state is more than that in the initial state. Sometimes SF_6 is also added to the gas mixture if extra electron quenching is required, since it is highly electronegative. Also the addition of SF_6 to the mixture reduces the chances of RPC aging [6].

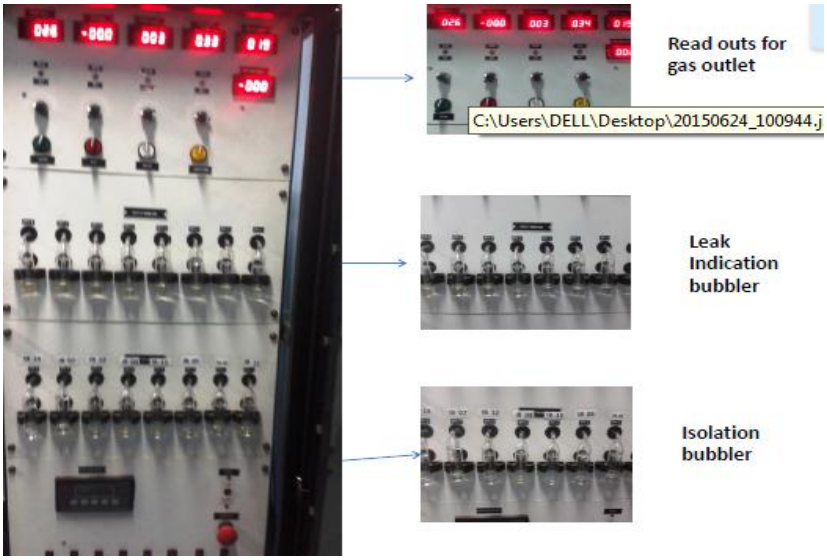


Figure 2.7 Image of the gas chamber

Gas is being provided to the Multi-gap RPC by a gas system (figure 2.7). There are three main components of the gas system as shown in figure 2.7 above which are briefly explained as below:

1. **Read outs for gas outlet:** It tells us about the amount of gas being applied by the system.

2. **Leak indication bubbler or Safety bubbler:** As it is clear from the name itself that safely bubblers indicates bubbling in the bubbler when there is some leak inside the detector. It protects MRPCs from the over pressure and takes care of back pressure which may damage MRPCs. These bubblers are made of borosilicate glass and with the help of a flexible Tygon Tube they are connected to a stainless steel tube. Each of the bubblers has nearly 5ml (~25 mm) of silicon diffusion pump oil having density of 1.08 g/cc at low vapour pressure at the room temperature. So when the proper inlet and outlet connections are made to the detectors, then there should not be any bubbling through the safety bubblers. The outlets of all the bubblers are connected to a common vent.

3. **Isolation Bubbler** Isolation bubblers having their working similar to that of the safety bubblers instead the bubbling in the isolation bubblers indicates the proper gas flow in the detector. This means that there is no leakage in MRPCs. They help to prevent the back diffusion of air in the MRPCs. Through each isolation bubbler gas mixture for each MRPCs flows. If there is no bubbling in isolation bubbler it indicates that there is some leak in gas or there is malfunctioning of the channel. All the bubblers output is fed into an exhaust manifold and then it is vented out.

Chapter 3

POSITRON EMISSION TOMOGRAPHY (PET) IMAGING

Positron Emission Tomography (PET) is a medicine technique that produces a three dimensional image of functional processes in the body. PET uses positron emitter as the radionuclide rather than a gamma emitter. The first positron medical image was made by Brownell and Sweet at Massachusetts general Hospital in 1951. Two NaI detectors were moved manually to scan brain tumours. In the 1960's and 1970's positron imaging devices used array of detectors. The first cyclotron for medical use was installed at Hammersmith Hospital, London, in 1955. Though PET technology is in trend for some decades mainly for the tumours in the human body but the high cost involved in the procedure has delayed and minimised its importance. The major PET technology nowadays is based upon the coincidence image produced by two 511 KeV back to back annihilation photons using ring geometry of detectors with Bismuth Germenate (BGO) [14].

PET measures the metabolic activity of cells and the functioning of tissues or organs in the human body. It uses radioactive chemical (or drug) called **Tracers**, to look at different organs in the human body. The tracer is a substance which gets collected in the cell, say cancer cell, and uses a lot of energy. During the test, the tracer liquid is injected in the body and it moves through different organs and gets collected in the body giving positively charged particles, positrons. The track of the positrons can be recorded and can be picturised. For example, for PET scan of brain, since the brain uses glucose for its metabolism, a radioactive atom is applied to glucose (i.e. FDG (18F-fluoro-2-deoxy-D-glucose). and radionuclide of type radioactive oxygen, carbon, nitrogen are used to check the blood flow and perfusion of an organ or tissue [15].

A significant impact in PET applications was the development of 18F-fluoro-2-deoxy-D-

glucose (^{18}FDG) at Brookhaven National Laboratory in 1976. It is a glucose analogue, metabolic imaging agent giving regional information of energy metabolism in brain, heart, tumours and other organs. ^{18}FDG, radioisotope has a half life of 109 minutes, which provides an appropriate decay time for searching tumours and meta states by patient whole body scan. In tumour cells, the actual rate of glucose utilization is enhanced if we compare it with the normal cells and this biochemical characteristic is utilized in PET imaging using FDG as a major workhorse.

Positron is an antiparticle of electron, which has mass equal to that of an electron but the charge is +1. Positrons are emitted by the breakdown of the radionuclide. Positron emission (or β^+) is a type of radionuclide decay in which a proton is converted into a neutron while releasing a positron and an electron neutrino. The positrons that are emitted have energy of the order of 1 MeV and have a very short range in human tissue (~1-2 mm). Once the emitted positron loses most of its kinetic energy through collisions with ambient particles, it can combine with electron and form a short lived entity called **positronium.**

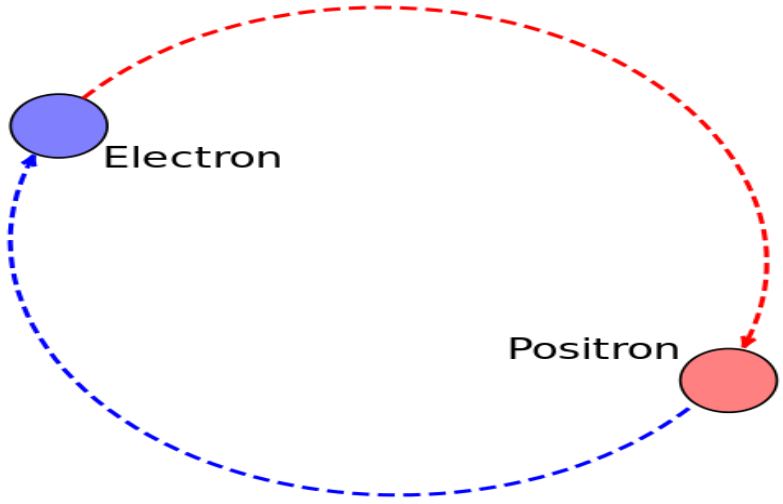


Fig 3.1: an electron and positron orbiting about their common centre of mass. This bound quantum state is known as **positronium.**

Positronium is a system where electron and its antiparticle positron, are bound together in an exotic atom, specifically an onium which is the bound state of particle and an antiparticle. This system is unstable and two particles annihilate each other to produce two gamma rays depending on their relative spin. The positronium produced rapidly undergoes annihilation reaction in which all energy of electron and positron pair is converted into radiation and

production of two photons takes place, each of energy very close to 511 KeV. [14]

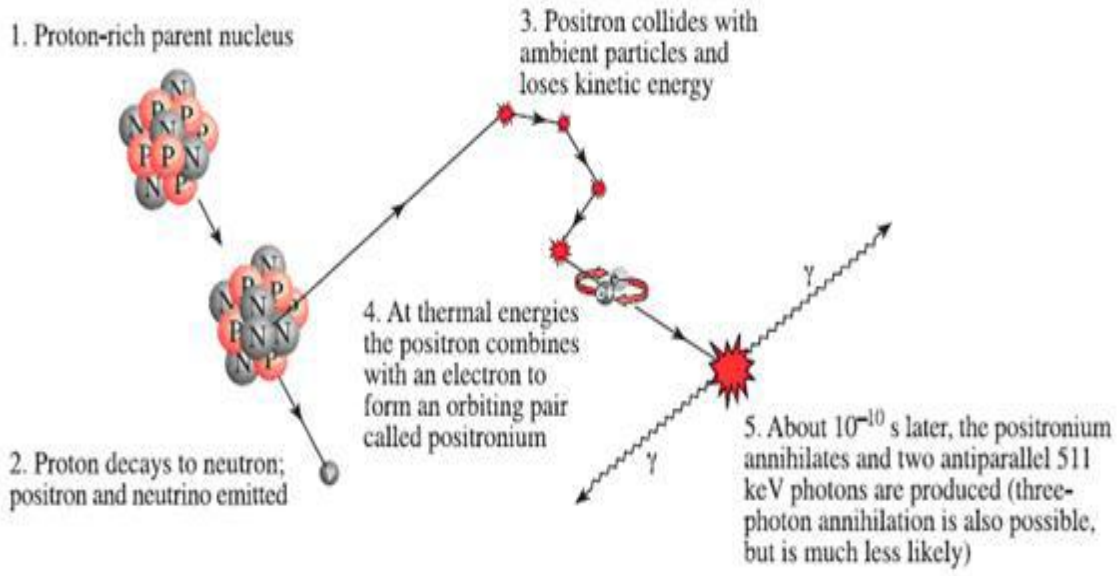


Figure 3.2: Diagram of positron decay and annihilation resulting in the two 511 KeV gamma rays which are detected for positron emission imaging. [14]

In order to conserve the energy and momentum, two photons are emitted in exactly opposite direction in the frame of positronium and to detect these photons, scintillation detectors say, bismuth germinate (BGO) and photomultiplier tubes are placed opposite and parallel to the source of positron emitter. These signals are passed through separate amplifiers and energy discriminating circuits. Through this process we can detect the coincidence event along the line joining the two detectors and each event is detected by a coincidence circuit with a narrow window, usually of 15 ns. Using PET scanning, millions of coincidence events can be detected and provides us information about the location of positron emitters within the patients.

3.1 Detectors used in PET

So far in PET imaging, mostly different types of scintillators are used (since they have very good stopping efficiency as well as the energy resolution). Most of the detectors are fabricated with some doping element to improve the yield of the photons. The emitted photons are to be detected in PET imaging having energy of 511 KeV, so the detectors which are to be used have some specialised characteristics.

These few characteristics of the detectors are to be considered before using it for PET technique. The increased stopping power of the detector enables it to efficiently absorb the total energy of 511 KeV of annihilated photons.

To choose a detector for PET, the following points should be kept in mind:

1. **Decay time of the scintillator:** The shorter time constant enables faster production of the signal after complete absorption. The slow decay time leads to increased detector dead time and high random coincidences.
2. **Detectors energy resolution:** Good energy resolution is needed to efficiently reject the events which may Compton scatter in the patient before entering the detector.
3. **Stopping power of the detector for 511 KeV photon:** Stopping power tells us about the mean distance travelled by photons until the energy deposition is complete.
4. **Attenuation length of the detector:** A detector with a short attenuation length will provide maximum efficiency in stopping 511 KeV photons.
5. **Signal to noise ratio:** Detector should have a capability to produce higher output per KeV so as to have good spatial resolution with a high encoding ratio.

3.2 Time of Flight (TOF) measurement

In Time-of-Flight (TOF) measurement, the precise time for each annihilation event is noted and each of the coincident events is detected and we calculate the time difference. The photon which is closer to the detector will arrive first, and the difference in arrival times helps us to analyse the location of the annihilation event along the line between the two detectors.
In PET, detection is performed by placing the number of detector elements around the ring geometry. The incident annihilation photons will interact with the detector which will absorb the photon energy resulting in the electrical signal. In this way, two annihilated photon pairs will be detected and will be connected through a virtual line, Line of Response (LoR).

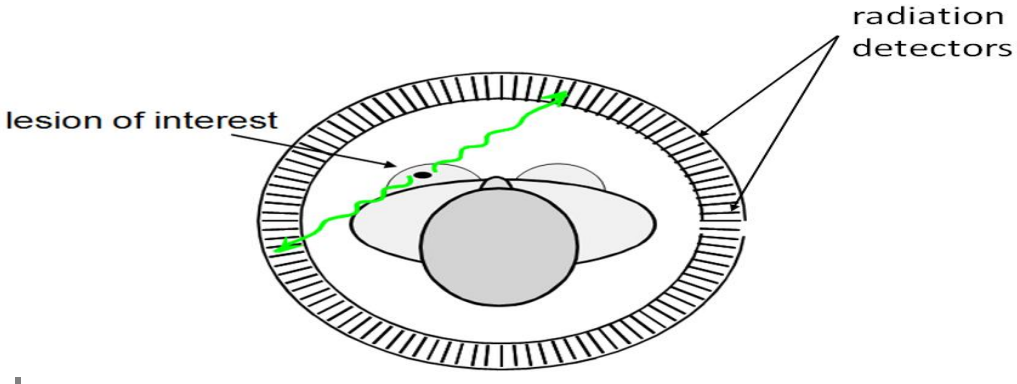


Figure 3.3: PET detectors showing positron annihilation [16]

In figure 3.3, the rings of detectors are placed around the object which detects the photon pairs, which are generated by the annihilation of positron. To detect the simultaneous photon events, PET detectors should have fast response.

The Time-of-Flight PET is a technique which exploits the time difference Δt at the time of detection of two photons and relates it with the position of the annihilation point Δx with respect to the centre of field of view which is given by formula:

$$\Delta x = c\Delta t / 2 \qquad (3.1)$$

Figure 3.4 explains the concept of detection technique that takes place in ToF. There are two scintillators and photo detector which are kept opposite to each other horizontally along the centre of Field-of-View. From the point of annihilation, we measure the distance Δx, using above formula. Once the annihilation takes place, photons will move toward the scintillator and is detected by scintillator kept opposite to each other. The photon with shorter distance will reach first and the one which is away will reach after some time. So by measuring the difference in the arrival of two photons in their respective scintillators, we measure the time of flight.

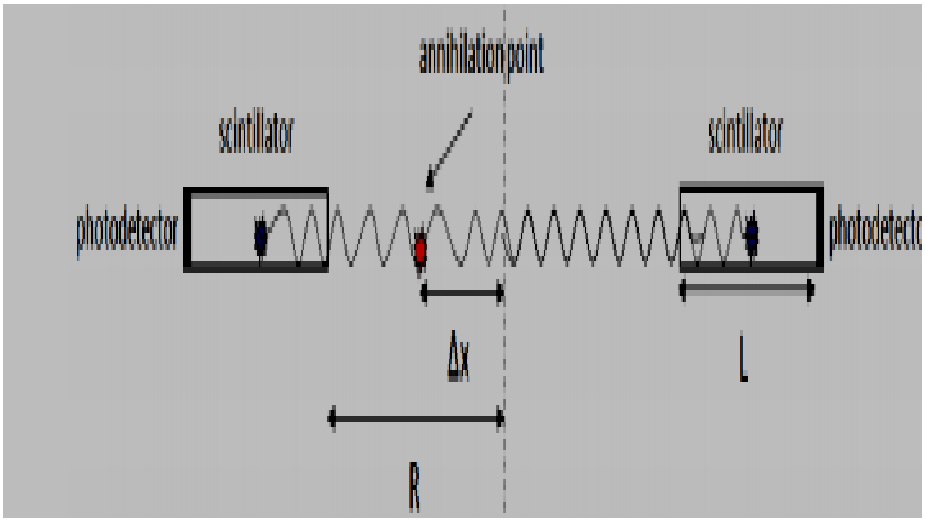


Figure 3.4: showing concept of Time of Flight [16]

3.3 Use of Time of Flight in medicine

In a PET detector, the scintillation crystal properties determine how precisely one can say whether the two photons are detected simultaneously or not. But we find uncertainty in the

arrival time and that uncertainty in the arrival time difference between two photons is known as the coincidence time resolution.

TOF has a vast application nowadays and the main advantage of TOF is in medicine. TOF is used in medicine mainly either to reduce the scan time or to improve the quality of image. Many tests were performed and we came to the conclusion that TOF information would reduce the image noise and we will get a clear picture on using TOF construction rather than a non- TOF construction. The clarity in the diagnosis can be seen with the help of the picture given below.

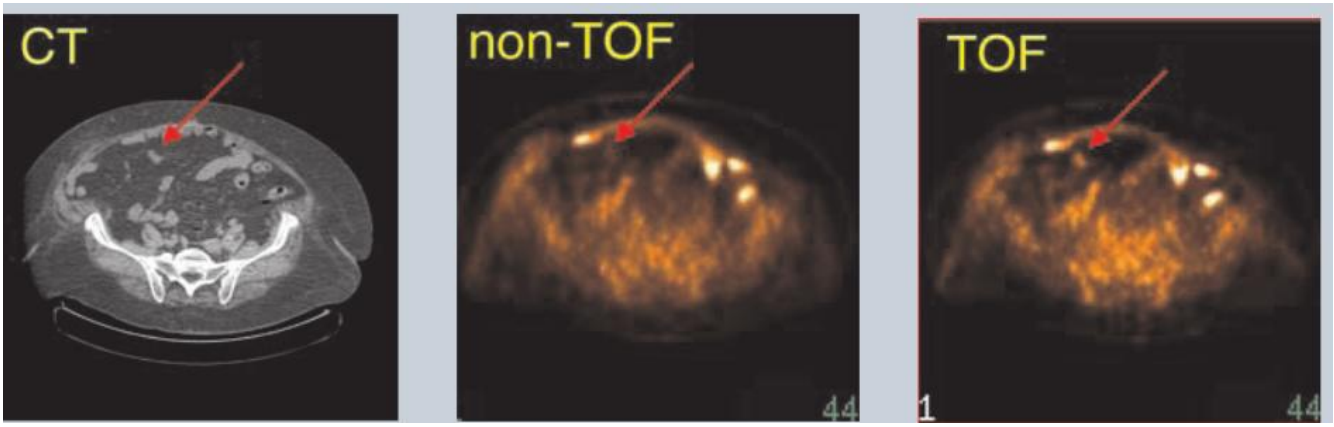


Figure 3.5: Image showing result of a heavy patient when analysed with CT, non-TOF, TOF [18]

In this picture, a heavy patient was diagnosed for colon cancer. The weight of the patient was 119 kg and 46.5 BMI. The analysis was done using CT (Computed Tomography), non-TOF and TOF and we found the results shown in figure 3.5. The analysis with TOF showed an improvement in lesion (a region in organ or tissue which has suffered damage through injury) delectability, as shown by the arrow in the figure.

The patient in this image was scanned for 3 minutes per bed position and in total there are around 10 bed-positions. So the patient is scanned for about 30 minutes. The main purpose of using TOF here was to improve the image quality or in other words, signal to noise ratio. The images for the lighter patients were also analysed with scan time as short as 1 minute per bed and we obtained the good quality image.

Caesium fluoride (CsF), Barium Fluoride (BaF_2) or Bismuth Germanate (BGO) scintillators, due to good time resolution are the candidate for TOF-PET. Presently due to practical

consideration, only BaF_2 is feasible for use as a scintillator in TOF-PET scanners.

However, since BaF_2 also has a very low stopping power, time-of-flight scanners have a reduced sensitivity leading to lower signal-to-noise ratios. Hence, then overall design of such scanners requires a careful trade-of between the scanner sensitivity and the time of flight (TOF) measurement so that the overall Signal to Noise Ratio for the scanner remains high. They are capable of meeting the high count rates of brain and study of heart using the short-lived isotopes. But the disadvantage of using these detectors is that they could not overcome the spatial resolution or sensitivity of conventional PET scanners. The coincidence time resolution of TOF scanners was expected to be between 500-750 ps but because of the difficulties in the electronics used and the accuracy of the scintillators, it was a difficult task to be achieved.

As shown in figure 3.5 above, CT and PET scan are performed simultaneously where CT unit is mounted at first followed by PET unit. Framework is same for both the units and is kept in a common imaging table. It is very clear from the above image that in PET scan a large section of the body can be scanned easily with more precision.

3.3.1 Merits of using PET over CT scan

Nowadays PET imaging is very much in trend for the diagnosis of tumours and cancers. There are some reasons for which PET is preferred over CT scan and some of them are explained below:

- In PET scan, we get a clearer picture of the point of tumour or cancer.
- Functioning of different biological processes is easy to determine in case of PET.
- In PET scan, early onset of disease can be detected by for tumour or cancer.
- With the help of PET scan, we can easily find out how effective is the treatment for the patient.

For the reasons mentioned above, PET scan is preferred over CT scan in case of nuclear medicine in high energy physics.

3.3.2 Risks involved in PET scan

In PET imaging, there are many chemicals which are injected in the body which may have some side-effects on human body and there can be many other risks involved. Some of them are discussed below:

- Since the radiotracers are injected inside the human body, they may be harmful for the

body but the dose injected is very less so it is acceptable for the diagnosis.

- In PET imaging, before going for the diagnosis and after the imaging, patient is informed about all the risks involved and clear picture is shown.
- There are chances of allergic reactions because of radiopharmaceuticals but the chances are very rare.
- When the tracer is injected inside the body, it might be a little painful at that time but the wound heels very easily.

3.4 Advantage of using MRPCs over scintillators for PET imaging

As we have already discussed that MRPCs are the gaseous detectors which are used all over the world for detecting the charged particles and are well known for their excellent time and position resolution. MRPCs are nothing but the advanced state of RPCs having smaller gas gaps with a better timing resolution. Nowadays scintillators are preferred all over for PET imaging but the main limitation is the high price of these crystal detectors which is not easily affordable for all. There are a few reasons why it is suitable to use MRPCs over scintillators for PET imaging and that are as follow:

- Fabrication of an MRPC is very simple and inexpensive and can be easily fabricated in any size. Fabrication of an MRPC is much cheaper than the crystal based detectors.
- Scintillators do not have good space resolution as the crystal used has thickness not more than 25 mm where as MRPCs shows a very good time resolution [15].
- Scintillators use Photo Multiplier Tubes (PMTs) as readouts but MRPCs detects charged particles directly and needs no PMTs.
- MRPCs show excellent time resolution of (~10 ps) as obtained in ALICE TOF project.
- With the help of read-out electronics, we can locate the specific position of an avalanche in case of MRPCs.
- There are no parallax errors at the time of detection of signals in MRPCs.
- MRPCs have fast response and because of this reason they are used for TOF-PET imaging in high energy physics.

Chapter 4

DEVELOPMENT AND CHARACTERIZATION OF 5-GAP GLASS MRPCs

4.1 Fabrication of 5-gap Glass (MRPCs)

We have fabricated two identical 18 cm x 18 cm 5-gap Glass MRPCs for the purpose of TOF-PET imaging. The steps involved in the fabrication are as follow:

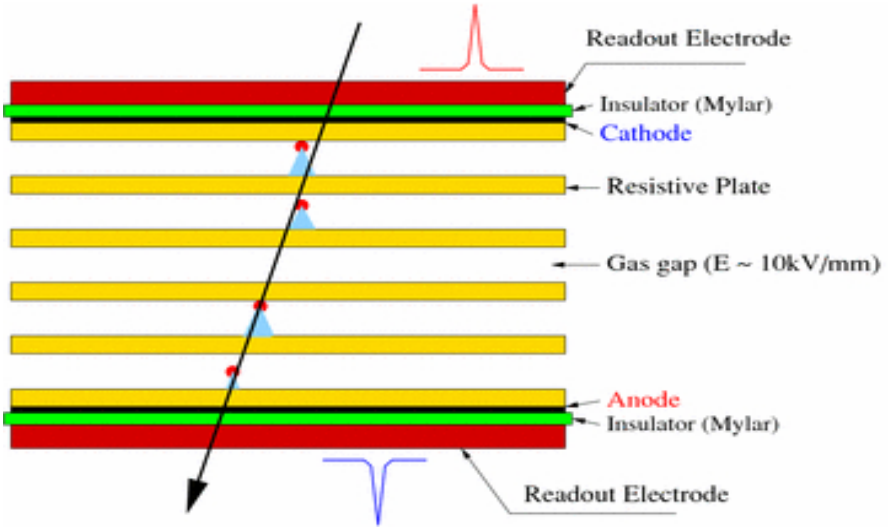


Figure 4.1: Schematic of Multi-gap RPCs (MRPCs) [19]

1. **Cutting and cleaning of Glass:** For a 5-gap glass MRPC, 6 equal sized glass electrodes each of thickness 750 microns were cut by the local vendors using the diamond cutter to the desirable size and all the four corners of the glass plates were smoothened using the jig to avoid the chances of spark. Glass plates were then cleaned thoroughly with the alcohol along with the gas nozzles, spacers, high voltage wires. The outer glass electrodes are taped with the kapton tape on the corners with 1 cm broad to reduce the chances of leakage in MRPCs.

2. **Conducting Graphite coating:** The outer electrodes are applied with the conducting graphite paint to increase the conductivity of the glass, rest all the plates are kept

floating between these two outer electrodes. A mixture of dry colloidal graphite and thinner in the ratio 1:1 are sprayed using a gun on the outer electrodes. Once these surfaces are coated the kapton tapes are removed (figure 4.5) and surface resistivity was measured for both the surfaces to ensure that surface resistance profile is uniform through the entire surface area of the glass plate. Surface resistance of the surfaces was measured using a resistance measurement jig (figure 4.2).

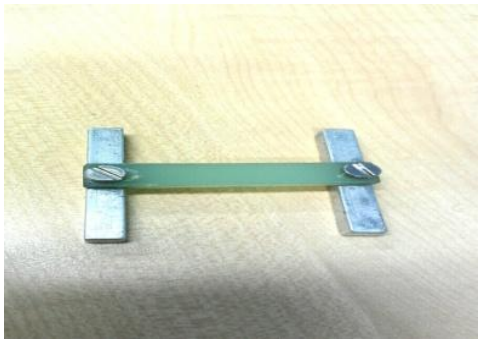


Figure4.2: Image of an aluminium jig

Surface resistance profile of both the surfaces is shown in figure 4.3.

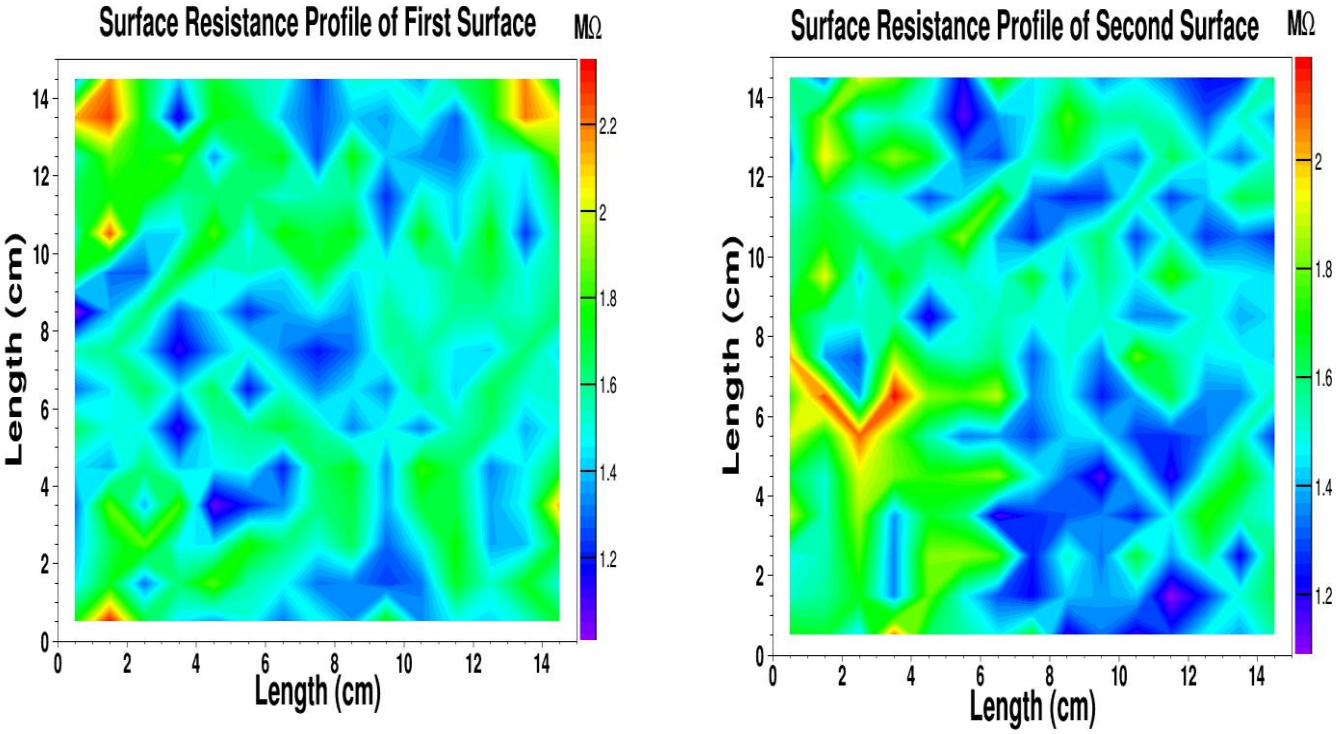


Figure 4.3: Surface resistance profile of top and bottom surface of MRPC (18cm x 18cm x 0.075 cm)

3. **Gluing of gas nozzle and spacers:** After the graphite coating, all the glass electrodes are kept in a highly evacuated perspex box (figure 4.4) one over the other and constant gas-gap of nearly 250 microns is maintained using spacers of this much height. Spacers are glued using BC600 optical cement glue. Firstly one of the graphite coated glass electrode is kept on the bottom surface of the box and then button spacers are glued on both sides of floating electrodes. In this way all the glass electrodes are set in the perspex box using the G-10 sheet spacers (4mm x 4mm x 0.25mm). On the diagonal corners of the perspex box gas nozzles are glued for the inlet and outlet of gases.

Figure 4.4: Image showing perspex box

4. **Gas Leak Test:** After gluing the spacers and the gas nozzles, leak test is performed to ensure against the leakage of gas through the detector. This test is performed by flowing a gas (freon or isobutane) at slightly higher pressure then the atmospheric pressure using gas leak detector. Wherever there is a leak, re-gluing is done on those areas.

5. **High Voltage Power Supply:** On the graphite painted outer electrodes, high voltage is applied. Positive voltage is applied on one side and an equal negative voltage is applied on the other side. In this way, one of the electrodes behaves as anode and other as cathode and a common ground is given to both.

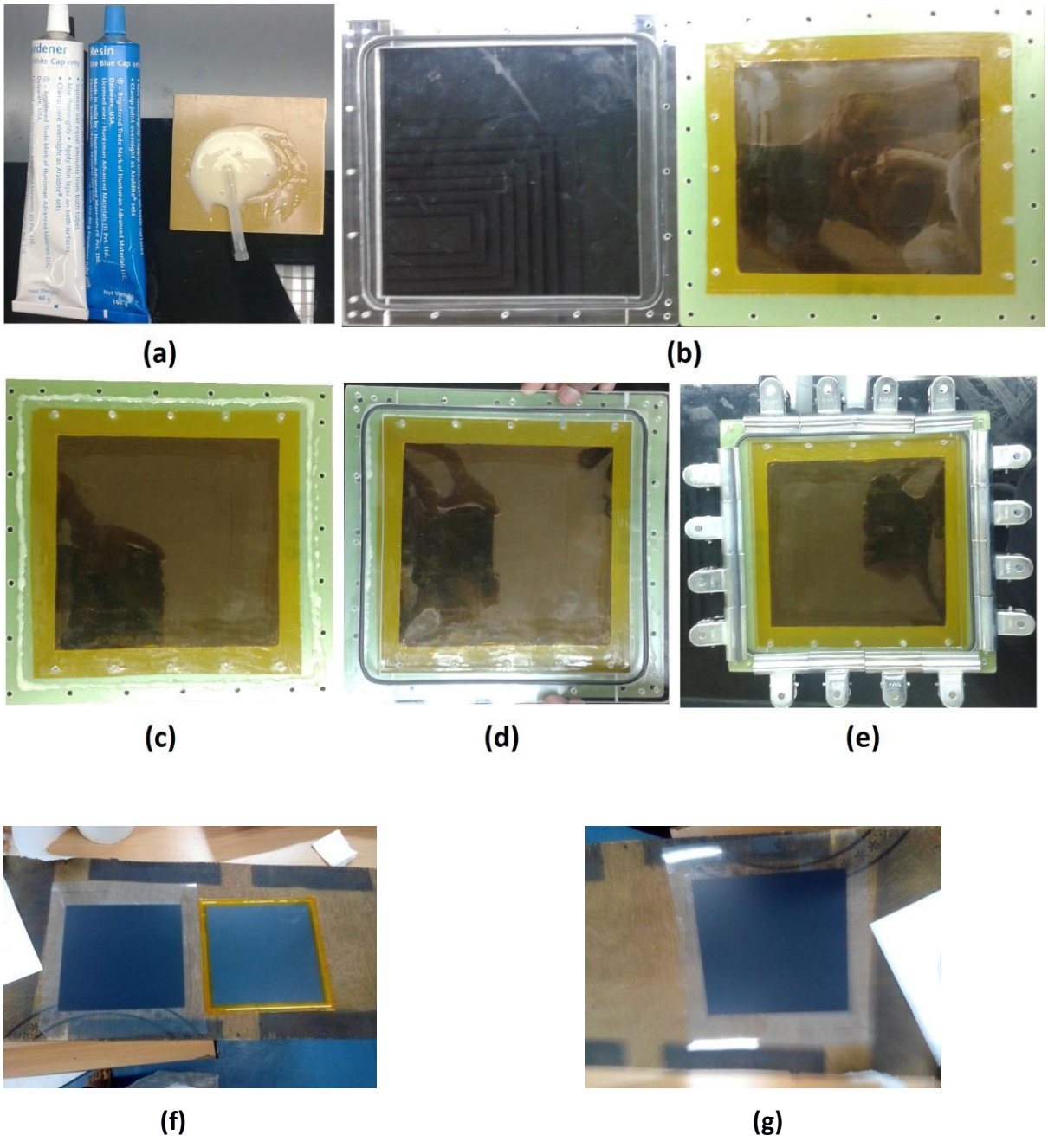


Figure 4.5: Steps showing fabrication of MRPC

4.2 Mounting and characterisation of Pick-up Panels

Pick-up panels are mounted on the outer electrodes of Multi-gap RPCs (MRPCs). The charges produced inside the gas volume due to the passage of a charged particle induces signal on the strips of the pickup panels. Pick-up panels are designed using a dielectric medium between two metallic layers. We have used pick-up panel (18 cm x 18 cm) made up of copper strips. Kapton sheets are used between the graphite coated electrodes and pick-up panels to avoid the direct contact between the two. The avalanche multiplied electron signals

are induced on the external pickup strips. Each pick-up strip has dimensions (18 cm x 2.5 cm). Itching is being done with the anhydrous iron chloride ($FeCl_3$) solution to maintain the gap of 0.5 cm between the copper strips in the pick-up panel. Figure 4.6 illustrates different steps involved in the itching process and figure 4.7 shows the actual image of the pick-up strips.

Figure 4.6: Steps showing fabrication of pick-up panels

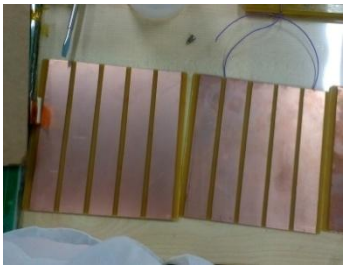


Figure4.7: Pick up strips used to tap the signals

4.3 Gases involved in MRPCs

For the glass MRPCs to be operated in avalanche mode, the choice of gas mixture is very important. Gases play a key role for the proper functioning of the detector as it effects the ionizations taking place. For a 5-gap Glass MRPCs in avalanche mode, gases involved are Freon, Isobutane and SF_6 if needed. In our case the ratio of Freon: Isobutane: SF_6 was 95:4.5:0.5 but this ratio is not fixed and can be varied accordingly. Let us discuss the roles of these gases:

- **Freon ($C_2H_2F_4$):** Freon plays a dual role, i.e. the role of an ioniser as well as electron quencher. Since freon contains many fluorine atoms and its molecular structure is also big, so it has a higher probability to undergo ionizations. Hence because of its big structure it acts as an ionizing agent.

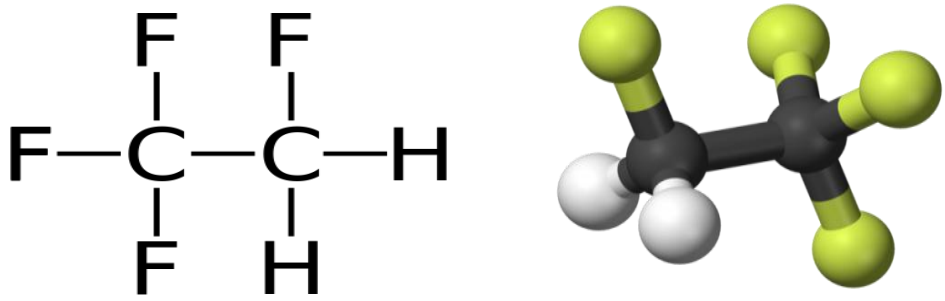


Figure 4.8: Images of Freon ($C_2H_2F_4$) [13]

Now when the ionizations will take place avalanche will tend to grow, so if we want to minimise the growth of an avalanche we need to control the electrons from undergoing multiple ionisations. Now since the fluorine is a highly electronegative gas it helps to serve the purpose. So because of large number of fluorine atoms present in freon, it acts as an electron quencher.

- **Isobutane:** Whenever the electrons will excite and then de-excite there will be emission of photons. Now these photons produced will also undergo ionisations which are undesirable. To stop the photons to go ionisations, a photon quencher is required. Isobutane is used as the photon quencher.

- **SF_6:** As discussed above that freon plays the role of an electron quencher because of the presence of large number of freon. But if the freon is not able to quench the enough electrons, in that case SF_6 is used containing higher number of fluorine. This will help to quench the electrons and to control the size of an avalanche.

4.4 Preliminary Results and their analysis

4.4.1 I-V Characteristics

A very important parameter for understanding the performance of the detector is to know about the leakage current of the detector at varying voltages. Leakage current is the rate of flow of discharge that develops and flows through the gas-gap of Multi-gap RPCs. Figure 3.10 shows an equivalent RPC circuit. Any RPC gas-gap contains two primary resistive

components i.e., highly resistive spacers (shows Ohmic behaviour) and ionization gas (behaves as a Zener Diode), both of which are connected in a parallel combination.

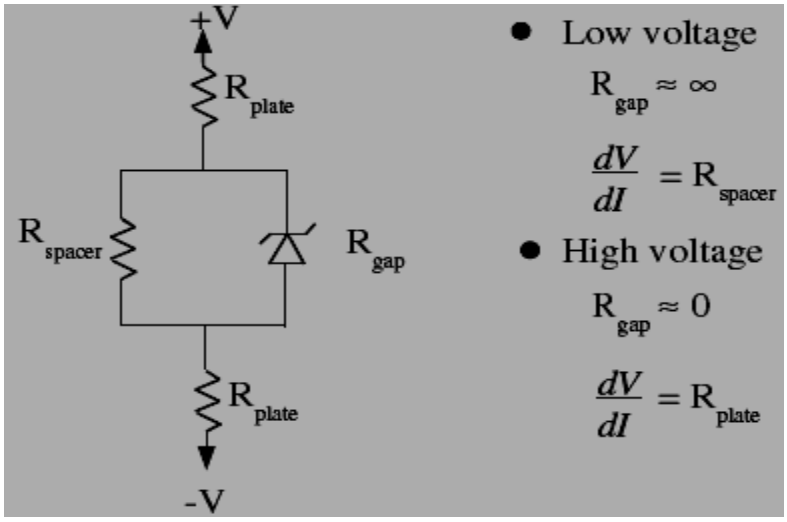


Figure 4.9: Equivalent RPC circuit [18]

Since at lower voltages, primary ionizations don't develop any avalanches and discharge, gas-gap offers infinite resistance and the current passes through the spacers. Therefore the slope over this region gives the conductance of the polycarbonate spacers

$$R_{gap} \approx \infty,\ R_{spacer} >> R_{plate} \Rightarrow dV/dI = R_{spacer} \qquad (4.1)$$

Breakdown of the curve occurs where there is sudden rise in the curve and current increases. This is because the ionization gas provides a conducting path to the current. So, in this case, the current flowing through the chamber is determined by the electrode resistance.

$$Rgap \approx 0 \Rightarrow dV/dI = R_{plate} \qquad (4.2)$$

I-V characteristics of any detector mainly gives us information about the gas breakdown and the operating voltage upon which detector should be operated. Figure 4.10 shows the I-V characteristics of the curve.

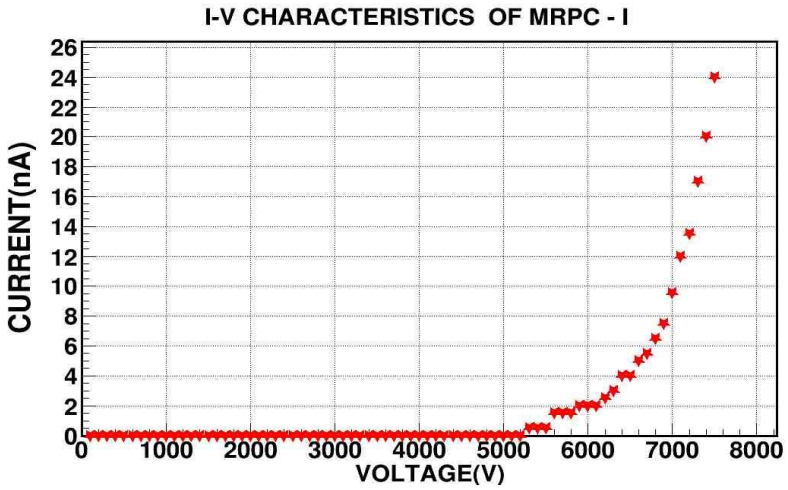


Figure 4.10: IV characteristics of (18 cm X 18 cm) Glass Multi-gap RPC when operated in Avalanche mode

Observations from the I-V curve:

1. Firstly we get the Knee voltage from the I-V curve, i.e., the voltage at which current shows a sharp increase from its leakage (almost zero) value and in turn we get the **breakdown voltage** of the gases.

2. IV curve also gives us the information about the resistance. The slope of the I-V curve gives us the resistance.

$$\text{Slope} = \text{Current} / \text{Voltage} \tag{4.3}$$

From Ohm's Law, we know that

$$V = IR \tag{4.4}$$

Equation (3.3) and equation (3.4) says,

$$\text{Slope of IV curve} = 1/R = \rho \text{ (resistivity)} \tag{4.5}$$

From I-V curve, we find two regions: One is the region before the breakdown, i.e. low voltage region and the other region is the region after breakdown, i.e. high voltage region. So we need to find the resistance of both the regions separately.

In the region before breakdown, gases will not be conducting, so in that region, the resistance

will be solely because of the spacers used.

$$\text{Slope} = 1/R = \rho \quad (4.6)$$

Also,

$$\rho = (Rl)/A \quad (4.7)$$

where,

R is the resistance we will get from the slope before the breakdown takes place.

l is the length of the spacer.

A is the total area of the spacer.

In the region after the breakdown, gas will start conducting. The resistance will be because of the gas as well as the thickness of the electrodes.

ρ (electrode) = ρ (overall resistivity of the chamber)= (R*l)/A

where,

R is the resistance we will get from the slope after the breakdown takes place.

l is the length of the electrode

A is the area

So, we can conclude that before the breakdown, the resistance will be the resistance of spacers and after the breakdown that will be of the overall chamber.

4.4.2 Time Resolution

Time resolution is the time interval of detection of two particles falling separately on the MRPC. When the signal falls on the detector, we expect it to fall on the same point. Only in that condition we can expect a sharp peak somewhere in the middle of the spectra. But this does not happen originally. We do not see the signal at the same point but instead we observe a Gaussian peak. This fluctuation in the original peak of the signal is because of the time jitter which may be because of the electronic components or different falling positions of the incoming particles on the pickup strips.

The time resolutions of the Multi-gap RPC modules were measured as described in the Figure 4.11 by using Phillips Scientific 7186 Time to Digital Converter (TDC). This TDC takes two

inputs: START and STOP signal, where START is always ahead in time than STOP. The time difference between these two signals is plotted which gives us a gaussian distribution. Note that for the spectra obtained, the observed time resolution (FWHM (observed)) includes the individual time resolutions of both, START (FWHM (START) and STOP signal (FWHM (STOP)). This can be expressed from the following equation:

$$\sigma^2_{observed} = \sigma^2_{START} + \sigma^2_{STOP}$$

So, if the time resolution of STOP or START is known, resolution of either can be obtained by using above equation.

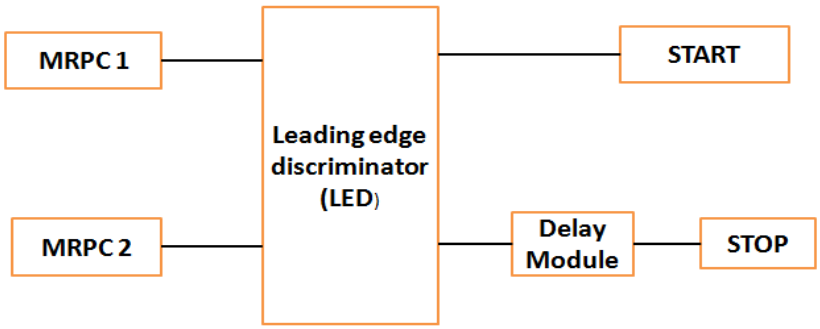


Figure4.11: Schematic representation of time resolution measurement setup

To calculate the time resolution of the Multi-gap RPC, we used two MRPCs i.e. MRPC I and MRPC II which are kept one over the other with some gap maintained in between them. Now to get the Time spectra of the detector, we need to give a START to one detector and STOP to the other. We also need the gaussian peak to develop in the centre of the plot. So, we give a 60ns delay using delay module to the MRPC-II and ultimately it goes to the STOP.

The setup was made as shown in figure 4.11 and using the equation above we calculated the time resolution for the MRPC1 by STARTing with MRPC-I and STOPing with MRPC2 at voltage 7800V(Figure 4.12) and time resolution of MRPC-II by STARTing with MRPC2 and STOPing with MRPC1 at 7800V(figure 4.13).

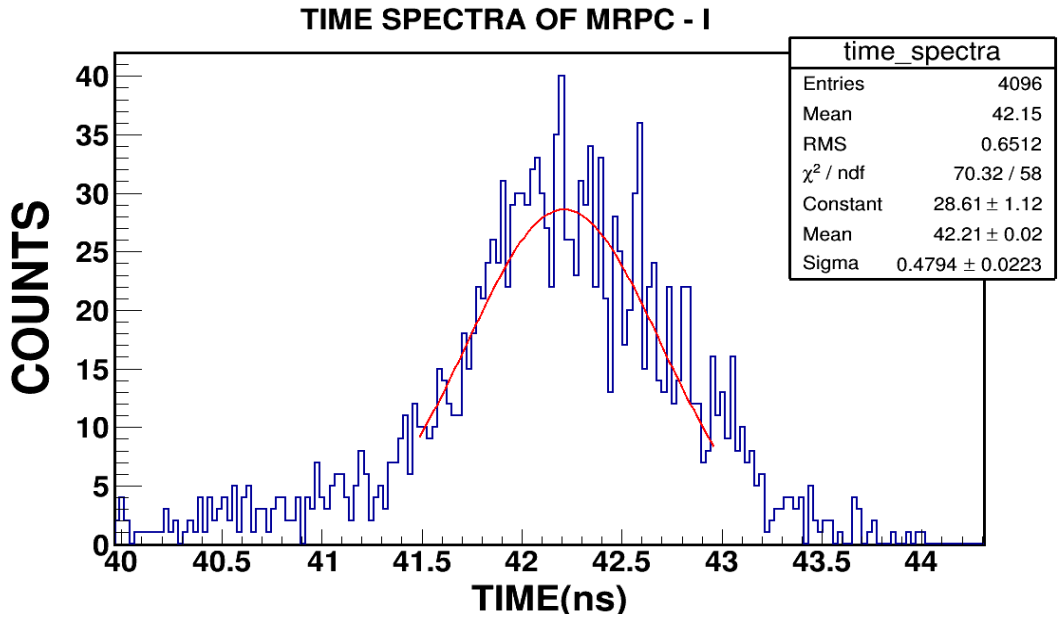


Figure 4.12: TDC spectra when START is with MRPC1 and STOP is with MRPC2 at voltage 7800V

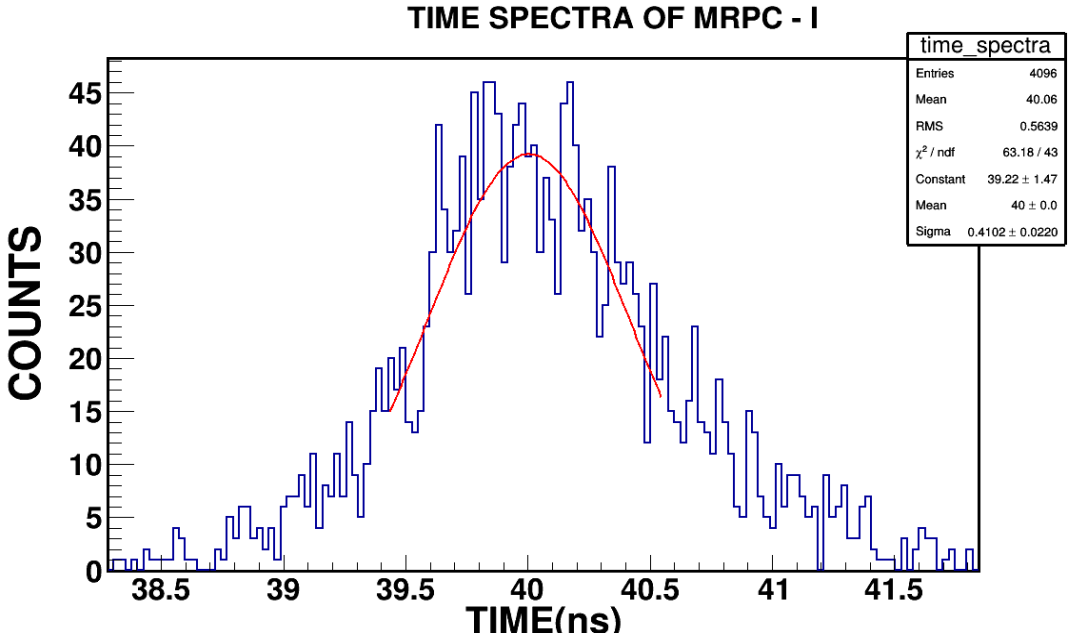


Figure 4.13: TDC spectra when START is with MRPC2 and STOP is with MRPC1 at voltage 7800V

By solving equation above, we get the time spectra as

$\sigma_{observed}$ ~ 340 ps (when START is with MRPC1 and STOP is with MRPC2)

$\sigma_{observed}$ ~ 290 ps (when START is with MRPC2 and STOP is with MRPC1)

Chapter 5

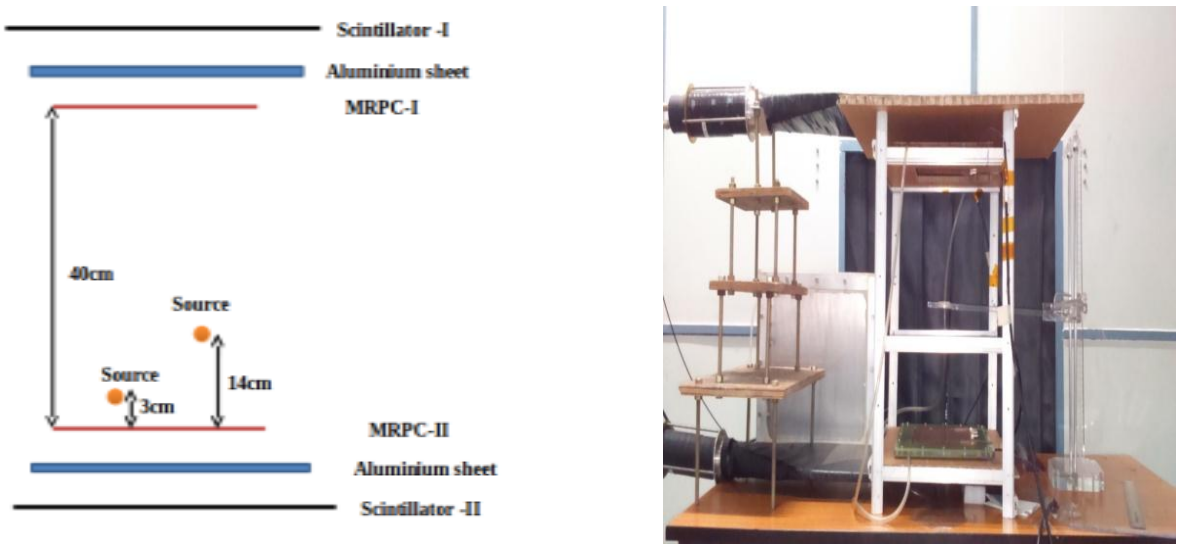
CHARACATERIZATION OF 5-gap MRPCs FOR TOF EXPERIMENTS

MRPCs are considered to be the most efficient detectors for TOF-PET imaging because of their good time resolution. The main reason to use MRPCs for PET imaging is to have highly précised timing. To obtain good time resolution, readouts i.e. both cathode and anode pick-up strips are suppose to be differential. When these pick-up strips tap the signal (511 KeV back to back photons in this case) then we calculate the time difference between the strips to obtain the actual hit position of the photons.

5.1 TOF setup and its working

In our lab, for the experimental testing of the detectors, we use Na-22 source which is highly radioactive. Its activity is 5 micro curie having half life of 2.6 years. It is a beta emitter which emits positrons. Figure 5.1 (a) shows schematic of the TOF setup in which we have used two identical 18 cm x 18 cm 5-gap glass MRPCs for detecting back to back photons.

As can be seen we have kept the source at two different positions which will be discussed later.



a) **b)**

Figure 5.1: a) Schematic of set-up b) Experimental set-up for TOF-PET imaging

We have kept two MRPCs one over the other at a distance of 40 cm from each other and the position of these MRPCs is fixed. Now to detect photons we use a source which emits photons. When the source is kept in between the MRPCs, back to back photons emitted from the source can be detected. But along with these photons, cosmic muons are always falling and efficiency of MRPCs to detect cosmic muons is very high (>90%) but at the same time MRPCs are very bad in detecting neutral particles (photons). If we look at the literature, gas detectors have efficiency of <1% to detect photons. So there is a high probability that cosmic ray will act as the background and we need to reduce that. We cannot stop the cosmic muons from falling on MRPCs but we can find a way to stop them from being detected. So we used two scintillators in order to reduce cosmic ray muons by VETO technique.

We have used two paddle scintillators whose area is slightly larger than the area of MRPCs and we have kept one scintillator on the top of first MRPC and other on the bottom of second MRPC. To ensure that photons should not reach the scintillators we have used 2 mm thick aluminium sheets. Then we go on varying the source at different positions and take the spectra. Figure 5.1 (b) shows the experimental set-up used for TOF measurement.

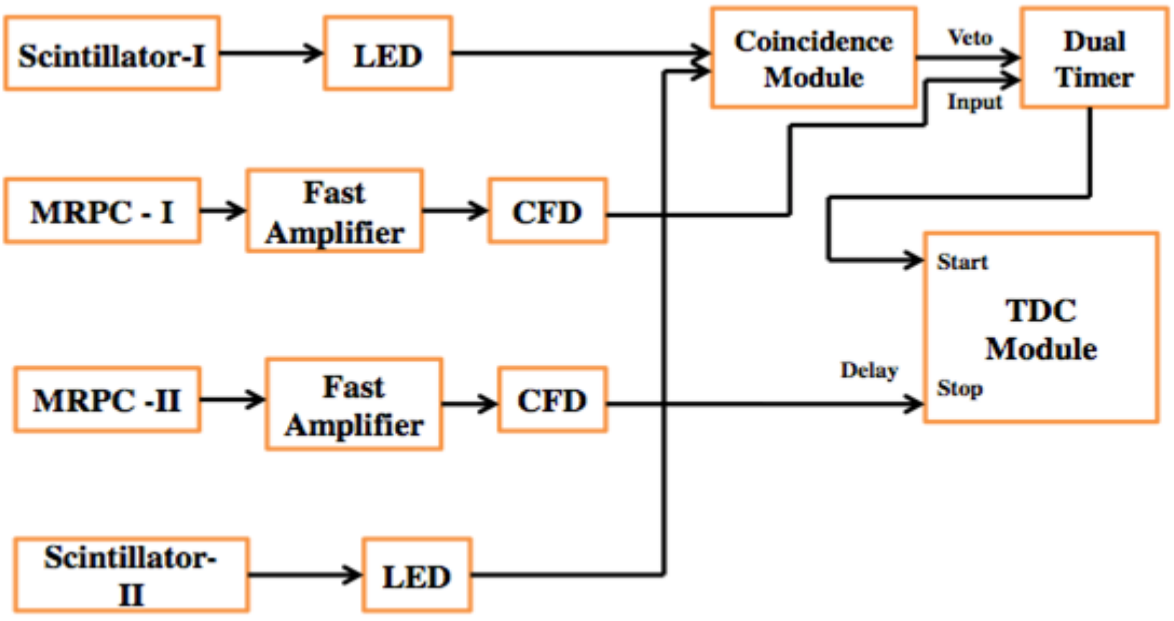


Figure 5.3: Electronic block diagram of the TOF set-up

Figure 5.3 shows electronic block diagram for the setup used to acquire the data. Since the

detectors produce analog signals and the modules can intake only the digital signal so we convert the analog signals coming from detectors (scintillators as well as MRPCs) into digital signals with the help of discriminators. But the signals produced by MRPCs are of very small amplitude so before digitising them, they are passed through fast amplifier of gain ~10. For scintillators we use Leading Edge Discriminators (LED) and for MRPCs we use Constant Fraction Discriminator (CFD). The detailed description of all the modules is available Reference 2. The digitising signals from both the scintillators are given to the coincidence module which gives an ANDed output. This ANDed signal of the scintillators goes to the VETO terminal of the dual timer and the signal from MRPC-I go to the INPUT terminal of the dual timer. Now VETO ensures that if you have any signal on both the scintillators then at the time of data acquition those events are rejected by using this dual timer module. Since we know that these scintillators are not 100% efficient, so we have ensured that even if one of the scintillator miss the signal and the other one catches, then with the help of offline analysis we have rejected those events also. So we acquire a TDC spectra in such a way that "MRPC-I. ($\overline{\text{Scintillator-I . Scintillator-II}}$) goes to START terminal of TDC module and MRPC-II after delay goes to the STOP terminal of TDC module. This TDC module will give us the timing information that whenever the MRPC-I gets a hit and at the same time MRPC-II also gets a hit, then the TDC module tells us that after how much time MRPC-II gets a hit with respect to MRPC-I. From this TDC spectra we can calculate the time difference that if we vary the position of the source then there will be a variation in the timing when there is a hit in MRPC-II with respect to MRPC-I.

Scintillator-I	**Scintillator-II**	**MRPC-I**	**Trigger**
0	0	1	1
0	1	1	1
1	0	1	1
1	1	1	1

Table 5.1: Trigger events for the START of TDC module

Trigger: MRPC-I. ($\overline{\text{Scintillator-I . Scintillator-II}}$)

In the Table 5.1 above we considered only those cases when both the MRPCs have signals it

can be a photon or a muon and we need to separate out the photon events from them. We consider all the cases step by step:

Case 1: If Case 1 is true then we have a hit in both the MRPCs and there is no hit in the scintillators, so there is a high probability of the event being a gamma event. In this case Trigger will be 1 indicating that there will be a very less probability of the event being a muon.

Case 2: In this case, there is a hit in one of the scintillators and both the MRPCs then there is a high probability of the event being a muon event and in this case Trigger will be 1.

Case 3: This case will be same as that of case 2 and there will be a hit on other scintillator and there is a probability of event being a muon event where value of Trigger will be 1.

Case 4: In case 4, there is a hit in all the detectors, in both the scintillators as well as in MRPCs and there is a high probability that the hit is because of muons.

Event 1, 2 and 3 of table 5.1 will be detected by the TDC module and since only event 1 ensures the event to be a photon event, event 2 and event 3 are removed during the analysis.

5.1.1 Variation of Noise Rate of MRPCs with and without source

To use the detectors for TOF-PET imaging, various tests are performed to check how the detectors behave in the presence and absence of source. Before the annihilation of electrons with positrons, positrons emitted from Na-22 source travels a very short distance (~ 1-2 mm inside the human tissue [10]) giving to back to back almost anti-parallel 511 KeV photons. Both the MRPCs kept one over the other at a distance of 40 cm are tested in four different configurations:

- without Na-22 source without amplifier
- without Na-22 source with amplifier
- with Na-22 source without amplifier
- with Na-22 source with amplifier

The Noise rate test using two identical 5-gap glass MRPCs was performed using with and

without source by showing the variation with the amplifier as sown in figure 4.4 and figure 4.5.

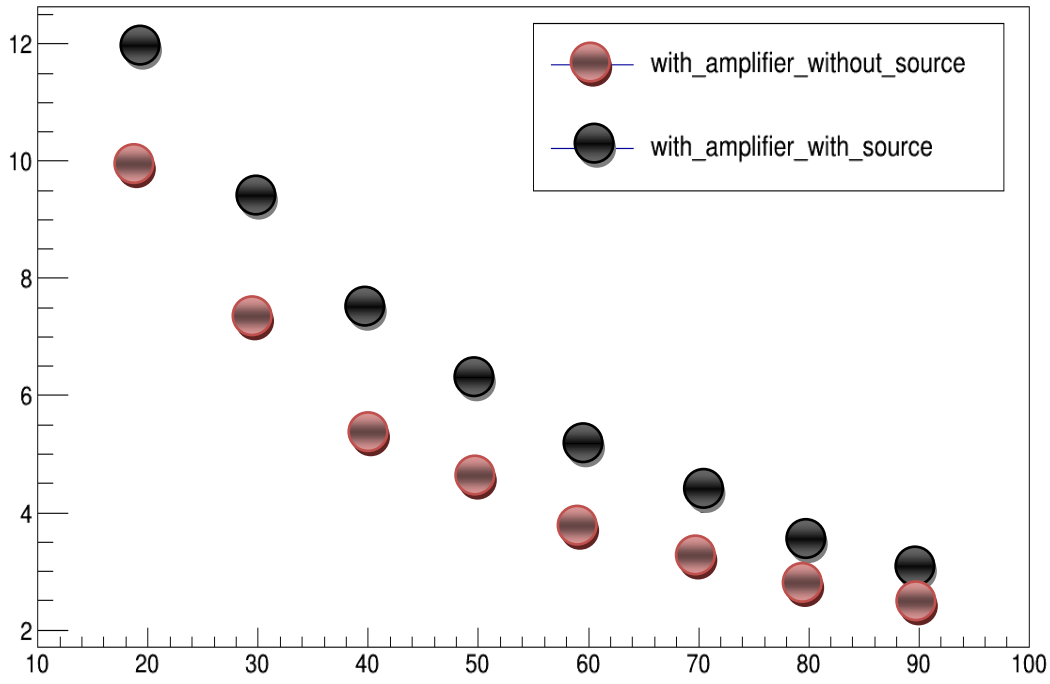


Figure 4.4: Threshold vs noise-rate plot using amplifier in the presence and absence of Na-22 source

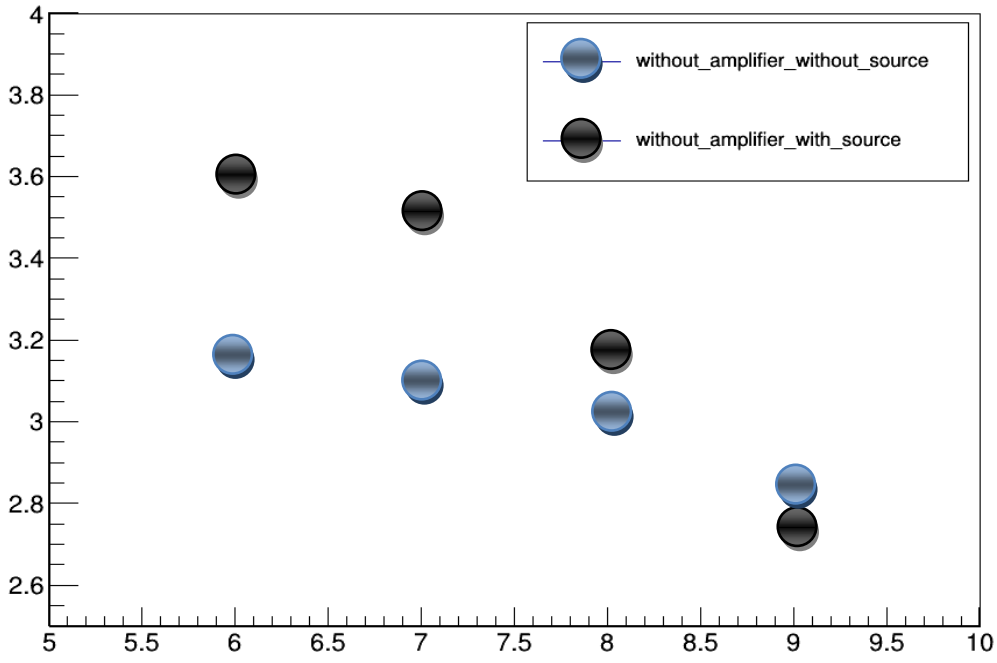
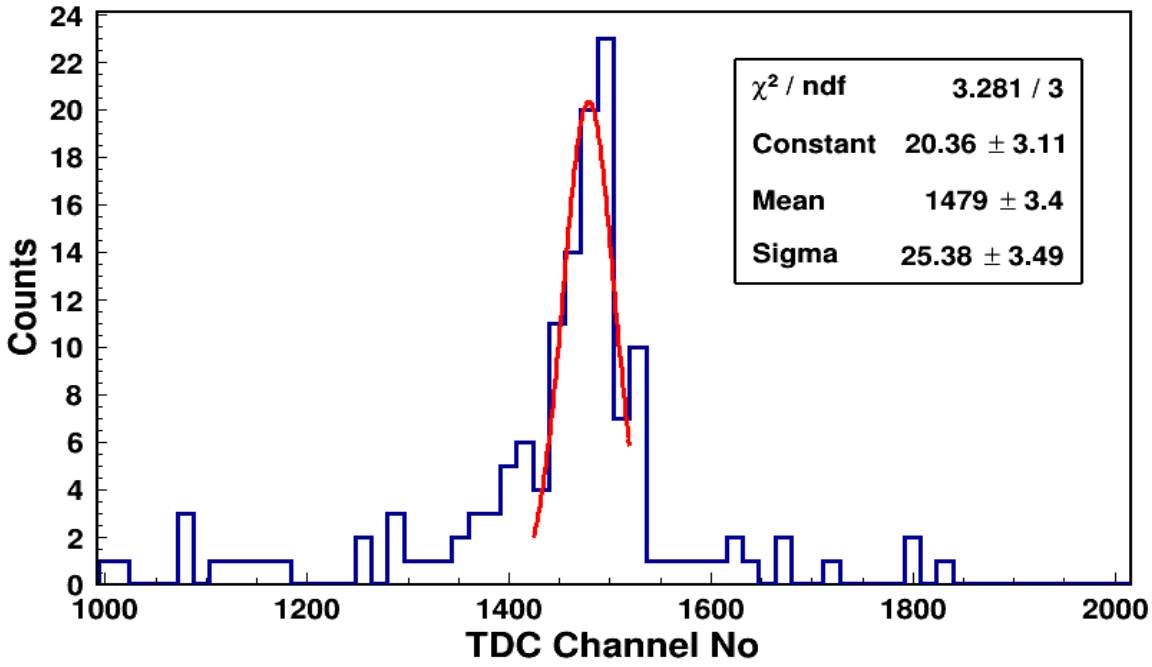


Figure 4.5:Threshold vs noise-rate plot without amplifier in the presence and absence of Na-22 source

Figure 4.4 shows that in the presence of amplifier, with the increase in the threshold voltage there is a decrease in the noise rate between the two detectors and figure clearly shows the presence of source.



5.2 Results and discussion

Figure 4.6 a) when the source is kept at 3 cm from MRPC-II

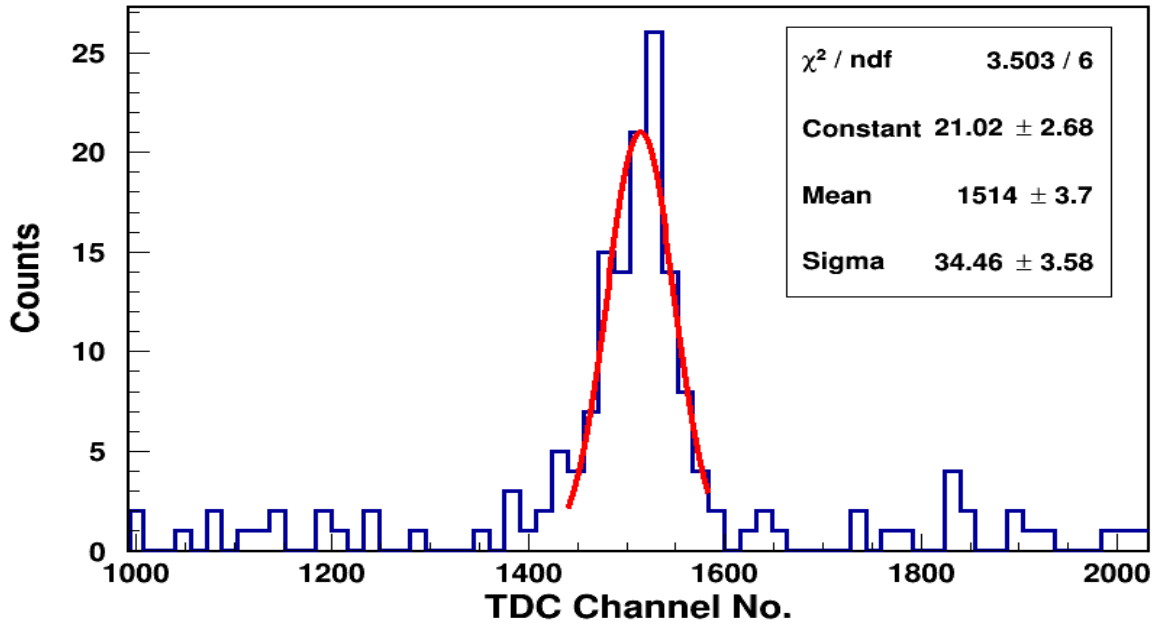


Figure: 4.6 b) when the source is kept at 14 cm from MRPC-II

Figure 4.6 above gives the data obtained for when the source is kept at 3cm (4.6(a)) and 14cm (4.6(b)) from MRPC-II. For this particular experiment, the START and STOP are MRPC-I and MRPC-II respectively. The graph represents counts versus channel number of 16-bit TDC. The plot is fitted with a Gaussian curve where χ^2/ ndf (number of degrees of freedom) ratio tells us about how good is the fitting of the plot and constant, mean (mean of the channel) and sigma are the Gaussian fitting parameters given by equation 5.1.

$$f(x) = p_o \times \exp(-0.5*((x-p1)/sigma)^2) \qquad (5.1)$$

where

p_0 is constant

Assuming that the TDC is linear and full scale of TDC is 100ns, each channel of TDC has the resolution of 24.4 ps. So the calculated mean time and sigma from the graphs are:

	I (Source is at 3 cm)	II (Source is at 14 cm)
Mean channel no	1478	1514

χ^2/ ndf 1.09 1.75

(χ^2/ ndf =1 implies the best fit)

5.2.1 Calculations

In the experimental set-up, distance between two MRPCs is 40 cm.

Speed of light is 30 cm/ns.

Case 1: When the source is kept at 3cm from MRPC-II

START 50ns STOP

Δt_1 = T stop – T start

=50- 14/30 + 3/30

=49.63 ns

Case 2: When the source is kept at 14cm from MRPC-II

Δt_2 = T stop – T start

= 50 – 3/30 + 14/30

= 50.367 ns

Time of Flight = $\Delta t_2 - \Delta t_1$

= (50.367 – 49.63) ns

= 0.73 ns

= 730 ps

Channel difference between the two different source position = 730ps / 24.4 (ps/ channel)

= 29.9

= 30 channels

Time of flight between the two source position is (3cm and 14cm) = 730ps (corresponding to 30channels)

If we see the plots in figure 4.6 X, there is difference of 36 channels and since each channel has the time resolution of 24.4 ps / channel. So the time of flight is calculated as (36 x 24.4) = 878.4 ps.

Comparison in the experimental and theoretical value gives us a time difference of 148.4 ps corresponding to 6 channel difference. This proves the suitability of the fabricated MRPCs for TOF measurements.

Chapter 6

CONCLUSION AND FUTURE OUTLOOK

Multi-gap Resistive Plate Chambers (MRPCs) are the most widely used gaseous detectors in experimental high energy physics and are well known for excellent time and spatial resolution. In addition to their application in HEP, they can be highly beneficial in the field of medical physics as well. MRPCs have a strong application in medical imaging and are mainly used for Time of Flight (TOF) Positron Emission Tomography (PET) imaging. So far scintillators are used for this purpose but MRPCs are preferred over them because:

- Good timing and spatial resolution.
- Relatively cheap due to its minimal fabrication material cost.
- Fabrication is easy and can be in any dimensions.
- Possess simple read-out electronics.
- Gives better Field of View (FOV).

We have fabricated two identical 5-gap glass MRPCs and tested them for TOF-PET imaging. For the MRPC characterization the Na-22 source (positron emitter) is kept between the

fabricated MRPCs separated by a distance of 40 cm. Both the MRPCs successfully detected the presence of source. Time of flight measurements give the time resolution of ~300 ps for the fabricated MRPCs. To check the suitability for the TOF-PET applications, we manually kept the source at different positions (3 cm and 14 cm) from the bottom MRPC and acquired the TDC spectra. The change in the spectra was noticed with the change in position of source and the values matched with the theoretical calculations..

Future Outlook

The present scintillator based PET provides metabolic information better than other imaging techniques like CT scan or MRI. Image quality (because of shorter FOV) needs to be improved and the radiation dose to the patients needs to be reduced. MRPC is a suitable candidate having better FOV hence giving a clearer image with good spatial resolution. The electronics associated with MRPCs is also simpler. MRPCs are also better suited for complete body PET imaging as it can be easily implemented over large areas resulting in less time and clearer diagnosis. For PET scan, a detector with a good time resolution is preferred because according to that value the coincidence time window (4 σ) is chosen. Lower coincidence time window will give lower random scatters and hence lower noise in the image. MRPCs have better time resolution then scintillation counters. There are some points which need to be worked on for implementation of MRPCs for PET imaging:

- We need to increase the time resolution of the MRPCs (~100 ps) to pin point the exact position of the melanin tissue (in brain). MRPCs fabricated in our lab have time resolution of ~300ps which need to be increased.
- MRPCs are the gaseous well known for the detection of charged particles but photon detection efficiency is very less (less than 1%). some ways are to be found out to increase the detection efficiency of photons in MRPCs.
- Compton scattering: As a result of positron-electron annihilation, 511 KeV photons are emitted and are scattered before detection. There is a decrease in actual photon energy (511 KeV) and direction of photon also changes because of compton scattering. As a result, the scattered event has no correlation with the actual annihilated photons which makes the detection difficult giving an inaccurate image. This need to be minimised.
- R & D must be done to determine the Line of Response (LOR) more precisely using MRPCs.

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