Chapter 3

Development of Multi-gap RPCs (MRPC) for the STAR experiment

This chapter focusses on the discussion about gaseous ionization detectors. The emphasis has been on the evolution of the parallel plate design and the Resistive Plate Chamber (RPC). The Multigap RPC (MRPC) design, which has been a natural progression in this field of detectors to improve timing resolution has been discussed in detail alongwith the fabrication and test results of the MRPC’s for the STAR-MTD project. A spin-off benefit of the detector R&D for the MTD project is to study the feasibility of MRPC’s as detectors in TOF-PET imaging. A preliminary effort in this direction, the fabrication and testing of small-sized MRPC prototypes with a positron-emitting $^{22}$Na source, has been presented here.

3.1 Gaseous ionization detectors

Detectors are devices that detect the presence of charged particles and/or electromagnetic radiation produced in high energy and nuclear physics experiments or from cosmic radiation. The first detection of ionizing radiation dates back to the 1890’s when Röntgen during his discovery of X-rays and subsequently Becquerel, during his accidental discovery of radioactivity, used
photographic plates as the detection tool. The ionizing property of X-rays were used to good effect by Madame Curie and later on by J. J. Thomson. The detection of charge liberated due to ionization necessitated a medium in which the charges could drift away from the point of generation under the influence of an electric field. This prioritised the choice of ‘Gas’ as the sensitive medium and hence the development of gas-filled detectors started.

The first gas-filled detector, the ‘Ionization Chamber’, used this principle of collecting charge liberated by X-rays in a gaseous medium in the presence of an electric field. The intensity of the ionizing radiation was found to be proportional to the amount of radioactive material used. The ionization chamber was used by Hess in 1910 for the discovery of cosmic rays [1]. Rutherford laid the foundation to gaseous ionization detector development for detecting ionizing radiation. His pioneering research led to a better understanding of the working principle of gas detectors. Rutherford and Geiger built the first cylindrical gas-filled device that made use of a metallic wire as an anode inside a cylindrical gas-filled cathode in the year 1908 [1][2]. The electrons released in the gas due to ionization drift towards the metallic wire anode under the influence of a potential difference between the electrodes. In the process, as the electrons reach the vicinity of the wire the electric field intensifies and the number of inelastic collisions undergone by the electrons increases exponentially. This exponential multiplication of electrons in the presence of a strong electric field is termed as the Townsend Avalanche, named after John Townsend for his extensive research on charge multiplication in gases due to collisions in the presence of strong electric fields. The detected charge signal is amplified as a result of the avalanche and is proportional to the charge created via primary ionization by the radiation incident on the detector. The gas detector developed by Rutherford and Geiger was hence adequately named as the ‘Proportional Counter’ [2]. Geiger and Müller developed a new detector based on the same principle in the year 1928. The detector was called the ‘Geiger-Müller Counter’ or simply, the ‘GM Counter’. The detector was robust and inexpensive and due to larger amplifications achievable with this detector as it was operated at higher electric fields, detection of single electrons was made possible [1][2]. With the passage of time and with the advancement of technology, the readout technology has
improved leaps and bounds compared to the rudimentary instrumentation existent during the development of these detectors.

Electromagnetic interaction is the most probable way in which charged particles interact with the gaseous medium. The passage of an energetic charged particle leads to ionizations in the gas medium and creation of electron-ion clusters. The phenomenon is called primary ionisation. If the primary electrons possess energy higher than the ionization potential of the gaseous medium, they create secondary electron-ion pair via ionizations. Gas detectors [3][4] work on this principle of ionisation and the direct collection of the ionisation electrons and ions produced by radiation passing through a sensitive (gas) medium. The mean number of electron-ion pairs created is directly proportional to the amount of energy deposited in the chamber by the through-going charged particle. The electron-ion pairs drift through the electric field towards the anode and cathode respectively where they are subsequently collected. On reaching the anode, the electrons pass through a resistor giving a voltage signal proportional to the charge deposited. The different regimes of gas detector operation based on the applied high voltage and the number of ion pairs collected has been discussed below [4].

At low applied voltages, when the electric field strength is insufficient to prevent recombination, the created electron-ion pairs recombine with each other. This is the Recombination region and the no. of ion pairs collected is less than that actually created.

With the increase in voltage, there is a suppression in the recombination of the ion-pairs and the total ionization produced by the through-going radiation is collected without any charge amplification. This is known as the region of Ion Saturation and the principle on which Ionisation chambers work. Signal pulse amplitude being extremely small, this mode requires sophisticated electronics for the measurement of radiation.

Beyond the ionization region, an increase in voltage leads to the onset of gas multiplication as the threshold field for secondary ionization (10^6 V/m) is overcome [4]. Charge amplification results in a proportionality between the number of incident and collected ion pairs and it is reflected through a linear amplification of signal pulse amplitude with the increasing number of
created ion pairs. This region of *true Proportionality* is the operating regime of the Proportional counter.

![Diagram showing modes of operation of gas detectors]

Figure 3.1: Modes of operation of gas detectors, in terms of the number of ions collected as a function of the applied voltage [3].

Upon further increasing the voltage, the linearity of operation is lost. At such high electric fields, the electrons are collected quickly on the cathode while a positive ion cloud is created within the gas gap owing to their larger mass and slower drift velocity. This space charge effect leads to a distortion of the applied electric field. This electric field dependent gas multiplication is the cause of the non-linearity observed in this mode of operation and hence the name region of *Limited Proportionality*. An increase in the number of created ion-pairs leads to an increase in the signal amplitude, but the dependence is non-linear. The avalanche mode of operation of Resistive Plate Chambers is in the region of limited proportionality.

At voltages beyond the region of limited proportionality, the space charge becomes the dom-
inating effect. A saturation is reached and the process of avalanche multiplication becomes self-limiting. Multiplication proceeds up to the extent where a certain number of positive ions build up a space charge within the detector that reduces the electric field such that further amplification is prohibited. Thus, the final detector output is independent of the incident radiation. This mode of operation is called the Geiger-Mueller mode and the region in which the GM counter works. The detector basically works as a counter of incident radiation without providing any information about its nature as it fails to differentiate between incident radiation of different energies.

An increase in the applied high voltage beyond the Geiger Mueller mode brings us to the Discharge mode, which is characterised by continuous discharge. Hence, this region is not used for detector operation. Fig. 3.1 is an illustration of the different regimes of operation of gas detectors.

The basic attributes of a gas detector are :-

- **Efficiency**: The efficiency of a gas detector is defined as the ratio of the number of particles detected to the total number of particles incident on it.

- **Position Resolution**: It is defined as the ability of the detector to localize particle trajectory within a small region.

- **Time Resolution**: The ability of a gas detector to distinctly detect two particles incident on the detector with a time separation is defined as its time resolution.

- **Dead Time**: The least attainable difference in time between consequent resolved hits on the same readout pad or channel of the detector is defined as the dead time.

The ease of construction, efficient handling and the economic nature of Gas detectors along with their excellent efficiency, timing and position resolutions make them front-runners for large area detection systems in high energy and nuclear physics experiments. The evolution of this field down the years has led to the development of more complex detectors that are efficient
and better in terms of performance compared to their primitive counterparts. The fill gas composition, detector operating conditions, the mode of operation, materials to be used for detector fabrication and detector geometry are optimised based on experimental requirements. A variety of gas-filled detectors are being used in experiments worldwide based on requisite detector parameters like rate capability, efficiency, timing and position resolution [5][6].

3.2 Evolution of the Parallel Plate Design in Gas detectors

The early gas detectors had cylindrical geometry, with a metallic wire kept at a large positive potential as the anode, while the surface of the metallic cylindrical tube kept at ground potential served as the cathode. Noble gases like Argon, or a mixture of Argon and a quench gas were typically used as the fill gas in these detectors. The purpose of the quench gas which is chosen to have high rotational degrees of freedom is to absorb the Ultraviolet (UV) photons, thus limiting the spread of the avalanche. The radial electric field E(r) due to the cylindrical geometry has a strong $\frac{1}{r}$ dependence on the distance (r) from the wire. Naturally, the field is most intense in the vicinity of the anode wire, at a distance of the order of the wire diameter. The avalanche multiplication happens once the electrons generated via ionization drift to this region of high electric field. The fluctuations in drift times results in poor timing resolution [6][7]. In order to achieve better time resolution, the planar geometry was considered. Planar geometry ensures a strong and uniform electric field throughout the sensitive area of the detector. Whilst electrons in case of a cylindrical wire chamber need to drift towards the high electric field region in the vicinity of the anode wire for avalanche multiplication to set in, parallel plate electrodes ensure instant avalanche multiplication of primary clusters created via ionization. As a consequence, the delay in signal formation due to electron drift times is averted and parallel plate detectors have excellent time resolution. In this case, the timing jitter is solely influenced by the fluctuations in the primary ionization, the avalanche growth times and the avalanche statistics [8][9]. The avalanche growth and the signal formation shall be revisited in a later section and discussed in greater detail for the parallel plate geometry. A brief history of the use of the parallel plate
design has been discussed in the following sections to shed light on the challenges faced and methods used to improve the detector parameters.

3.2.1 The Keuffel Spark Counter

The first gas-filled detector to utilize parallel plate electrodes and a uniform, high electric field is the Keuffel Spark Counter [10][11]. A uniform electric field of 1-3 kV/2.5 mm is provided by high voltage applied between two parallel Copper electrodes with a gas gap of 2.5 mm. A mixture of Argon and Xylene kept at a pressure of ~ 500 mbar acts as the sensitive medium. A through-going charged particle ionizes the gas and the uniform electric field immediately triggers the avalanche multiplication. The charge build-up inside the gas gap develops into streamers and sparks. Although the uniform electric field improves the time jitter, the metal electrodes pose the disadvantage of getting short-circuited by the sparks. This shortcoming is overcome by using a switching-off circuit, that stops sparks from shorting the electrodes at the expense of detector rate capability. Large area operation of the counter is impossible as the spark discharge energy being proportional to the chamber area, damages the metallic electrodes. The typical dead times measured for the Spark Counter are a few ms, required to recharge the electrodes via the high voltage power supply. This detector has a much improved time resolution (~1 ns) compared to the resolution achievable with the GM Counter (~100 ns) [8].

3.2.2 The Pestov Spark Counter (PSC)

The Pestov Spark Counter [12][13] shown in Fig. 3.2, is a gas-filled, parallel plate detector with an extremely small gas gap ~ 100 μm. Unlike the conductive electrodes used by Keuffel, this detector was the first to make use of resistive electrodes. The resistive anode used in this detector is a special glass plate of volume resistivity 10^{10} Ω-cm, while the other electrode was metallic. In the presence of the strong electric field, the avalanche transforms into a streamer but the detector does not run the risk of getting short-circuited. The streamer affects only a limited region of the anode due to its high resistivity, while the rest of the detector remains active.
The gas mixture used for the operation of this detector had high UV absorption capability that prevents UV photons from spreading the discharge.

![Diagram of Pestov Spark Counter](image)

Figure 3.2: Schematic diagram of the Pestov Spark Counter [14].

Very high detection efficiency is achieved by mounting the detector on an aluminium vessel, maintaining it at a large pressure of 12 bar which ensures large primary ionization in the small gas gap. A timing resolution as good as $\sim 35$ ps is obtained by the detector along with an excellent noise rate of $\sim 0.2$ Hz/cm$^2$ [14][15]. The limitations of the detector arise from the mechanical constraints imposed on its operation (high pressure) and the lack of availability of the non-commercial glass electrode.

### 3.2.3 Parallel Plate Avalanche Chamber

The Parallel Plate Avalanche Chamber (PPAC) is a gas-filled detector with a gap thickness of 500 $\mu$m to 2 mm maintained with suitable spacers between electrodes. The detector uses a variety of electrode material, from metallic plates to metallized ceramics and plastics. As is evident from the name, this parallel plate detector operates in the avalanche mode unlike the streamer/spark mode (to be discussed in detail in Sec. 3.3.3) operation of its predecessors. The
avalanche mode operation maintains a low device gas gain of $\sim 10^2$ to $10^5$ with a proper fill gas choice and prevents streamer formation. This keeps the discharge probability of the detector for minimum ionizing particles down to $10^{-5}$ and improves the rate capability upto 10 MHz/cm$^2$ [16]. The other advantage is the timing resolution of the detector $\sim 100$ to 250 ps [17][18]. The operation at a low gain has limitations in terms of small signal strength ($\sim 1 - 10$ fC) [18] that affects detector efficiency and the signal-to-noise ratio. The detector fabrication is non-trivial and the large scale use of the PPAC technology is questionable due to the above limitations [19].

Keeping in mind the limitations of the previous generations of parallel plate detectors, R. Santonico and R. Cardarelli in the year 1981 conceived a new detector called the Resistive Plate Chamber [20] and used resistive plates for its construction. The RPC is the basis of this thesis and has been discussed in detail in the next few sections.

### 3.3 Resistive Plate Chamber (RPC)

Designed as a better alternative to the Parallel Plate Avalanche Counter, the Resistive Plate Chamber (RPC) is fabricated with resistive plates as electrodes. Locally available, inexpensive materials like Glass and Bakelite (phenolic paper laminates) which typically have high volume resistivity ($\sim 10^9 - 10^{12}$ $\Omega$cm) are chosen as electrodes. The gas gap is defined using polycarbonate spacers of high resistivity ($> 10^{13}$ $\Omega$cm) sandwiched between the two resistive electrodes. The through-going charged particle ionises the gas which leads to an avalanche in the presence of the strong electric field. Highly resistive electrodes prohibit the flow of electric charge from the high voltage power supply to maintain this discharge. The discharge between the plates is therefore quickly quenched via a drastic reduction in the electric field in a small area. Typical discharge time scales are $\sim 10$ ns while the charging up of the plates depends on the time constant ($\tau$),

$$\tau = \rho \varepsilon_0 \varepsilon_r$$  \hspace{1cm} (3.1)
which depends on the electrode volume resistivity ($\rho$) but is independent of the detector dimensions [5][6][21]. $\varepsilon_0$ and $\varepsilon_r$ are the dielectric constant of the gas and permittivity of free space respectively.

As an example, the time constants for the bakelite ($\rho \sim 10^{10}$ $\Omega$-cm) and glass ($\rho \sim 10^{12}$ $\Omega$-cm) electrodes are $\tau \sim 10$ ms and $\tau \sim 1$ s respectively [6][8].

As the charge-up time is much higher compared to the discharge time, the area of the detector affected by the discharge ($\sim 0.1$ cm$^2$)[20], called the dead area, behaves as an insulator and remains inactive during this period of time ($\tau$, the dead time). The remaining area of the detector, however, is unaffected and retains its sensitivity to charged particles. This property of resistive electrodes vastly improves their rate capability. The fact that bakelite electrode resistivity is $\sim 100$ times less than glass electrodes, the rate capability of detectors using bakelite electrodes is proportionately higher. Glass electrodes with low resistivity values are being used currently for high-rate applications.

A schematic of a single gap RPC is shown in Fig. 3.3. Built using parallel plate electrodes of either glass or bakelite, electrodes are separated by polycarbonate spacers to define the uniform gas gap.

![Schematic diagram of a basic Resistive Plate Chamber](image)

Figure 3.3: Schematic diagram of a basic Resistive Plate Chamber taken from [8]
The high voltage is applied to the outer surface of the electrodes via conducting contacts that produces a uniform electric field in the gap. A thin graphite layer of surface resistivity \(\sim 1 \text{ M}\Omega/\square\) is painted on the external surface of the electrodes to permit the application of high voltage. The avalanche multiplication of the electrons and the movement of the charges inside the gap induces a signal on external metallic pick-up strips. The pickup strips behave like transmission lines and are isolated from the HV electrodes with a layer of insulator. Signals in gaseous detectors are induced signals due to the motion of charges within the sensitive volume and the signal persists till the charges arrive at the electrodes [2]. The readout strips on the two sides of the chamber can be placed perpendicular to each other, to provide the x- and y-co-ordinate of the through-going charged particle. The mode of operation of the detector which has been discussed in a later section determines the sensitive gas mixture to be used and the voltage to be applied on the detector.

The schematic shown in Fig. 3.4 highlights the difference between detectors with cylindrical geometry and parallel plate geometry in terms of avalanche growth and signal generation.

![Figure 3.4](image)

**Figure 3.4:** Illustration of the difference in avalanche growth and signal generation between a) a cylindrical wire chamber and b) a parallel plate detector [14]

RPC’s have better timing resolution compared to cylindrical wire chambers. This arises
from the uniform electric field in RPC's which results in instant avalanche multiplication as opposed to the \( \frac{1}{2} \) field dependence in wire chambers that introduces time fluctuations due to the drift of electrons to regions of strong electric field close to the anode wire for the initiation of the avalanche. Separate subsections in the thesis have been dedicated to discussions about the avalanche multiplication and signal generation in an RPC, specifically in a detector of 2 mm gas gap and the different modes of operation.

3.3.1 Choice of the Fill gas used in RPC's

The gas gap acts as the sensitive medium for particle ionization in a gas detector. The choice of the fill gas for an RPC, or for that matter any gas detector, is critical. The phenomenon of avalanche multiplication develops in practically all gases and hence any gas or a mixture of gases can ideally be used as the sensitive medium. However, there are certain criteria that must be satisfied, e.g. operation at low voltage, high gas gain, high rate capability, extended lifetime, swift recovery [22]. Noble gases that do not take part in chemical reactions are ideal choices for fill gas as their high specific ionization at low electric fields for charged particles, ensures a low operating voltage. Argon being the least expensive in the family of noble gases, serves as the perfect choice for the ionizing component. Detector operation with only Argon as the sensitive component has the disadvantage of transition to the discharge mode at gas gains \( \sim 10^3 \text{-} 10^4 \). During the passage of through-going radiation, ionization and excitation of Argon atoms occurs simultaneously. The excited Argon atoms return to the ground state via radiative processes. The emitted photons create undesirable secondary ionizations within the gas gap that enhance avalanche to streamer transition probability. This feature prompted the use of polyatomic molecules with rotational or vibrational degrees of freedom that dissipate the photon energy via non-radiative processes, thus enabling detector operation at high gas gains. These gases are called quenchers. A mixture of a noble gas and a quench gas (e.g. Methane-C\( \text{H}_4 \), Isobutane-i-C\( \text{H}_4 \text{II}_10 \)) allows stable detector operation at high gas gain. An electronegative additive is introduced in the gas mixture to serve as the electron quencher. Their primary function is to quench energetic electrons and

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prohibiting them from creating new avalanches elsewhere in the sensitive medium [22]. Freon and SF$_6$ are best examples of electron quenchers used in gas detector gas mixtures, especially RPC’s. The high atomic mass and cluster density of Freon, makes it a suitable ionizing gas for small-sized gaps operated in the avalanche mode. The large number of primary ionization electrons, especially the number created closest to the cathode produces detectable avalanches and maximises detection efficiency. A gas mixture containing Freon as the ionizer (R134A, eco-friendly), i-C$_4$H$_{10}$ as the photon quencher and traces of SF$_6$ as the electronegative electron quenching component serves well for the avalanche mode of operation of MRPC’s.

3.3.2 Avalanche Multiplication and Signal generation in RPC

The basic signal generation principle in case of gas-filled detectors like the RPC is based on ionization in the gas and the avalanche multiplication of the electrons [23]. In the presence of strong electric field (few kV/cm), the liberated primary electrons are accelerated to sufficient energies to create further ionizations in the gas gap. This phenomenon of multiplication of free electrons created via ionisation is termed as the Townsend avalanche. Due to the distinct drift velocities of electrons and ions (a factor of 10$^3$ higher for electrons) [7], owing to their much smaller mass, the shape of an avalanche is like a liquid-drop (Fig. 3.5), with a tail of positively-charged ions and electrons located at the head.

The Townsend equation governs the fractional rise per unit path length of electrons and is given as :

$$\frac{dn}{n} = \alpha dx$$  \hspace{1cm} (3.2)

where, $\alpha$ is the first Townsend coefficient for the gaseous medium. The value of $\alpha$ is otherwise field dependent, but, for the parallel plate scenario of uniform electric field, its a constant. The solution of Eq. 3.2 yields the number density of electrons as a function of distance as follows : 

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where, $n_0$ is the initial number of electrons and $x$ is the distance between the anode and the point where the primary ionization cluster is created. The number of electrons in an avalanche, therefore, increases exponentially. Let us take the example of a standard RPC of 2 mm gap thickness (d) subject to a strong uniform electric field (E). As equation 3.3 suggests, the total number of electrons created in an avalanche depends on the distance $x$. So, naturally, an electron starting to avalanche from the cathode, that traverses the whole gap thickness of 2 mm will accumulate a greater number of electrons in its course and hence generate more charge compared to the case when the avalanche starts at a distance of 0.5 mm from the cathode. This fact has been suitably illustrated in Fig. 3.6.

The majority of the electrons and ions are created at distances close to the anode during the course of the avalanche. Electrons drift quickly towards the anode and induce the fast component ($q_{fast}$) of the signal. The slow moving ions drift towards the cathode and induce the slow component ($q_{slow}$) of the signal. The total induced signal ($q_{total}$) is the sum of the fast and
Figure 3.6: Charge development in a 2 mm gap RPC with the avalanche multiplication starting at two different positions a) the avalanche starts at $x = 0$ and traverses the entire 2 mm gas gap and b) the avalanche creation is at $x = 0.5$ mm from the cathode and travels 1.5 mm in the gas gap [14].

the slow components and is related to the fast signal as [24].

$$q_{fast} = \frac{q_{total}}{\alpha \cdot d} \tag{3.4}$$

As will be discussed in detail in the following section, to maintain the avalanche mode of operation the limiting value of $\alpha \cdot d$ should be $\sim 20$. This limiting value is obtained when the electron avalanches the entire gap thickness and the number of electrons generated in the avalanche as given by Eq. 3.3 is $\sim 10^8$. This is equivalent to a total charge of 16 pC within the gap and a fast signal component equivalent to 800 fC. Similarly, when the primary ionization takes place 0.5 mm away from the cathode and the electron avalanches a distance of 1.5 mm within the gas gap, it generates $\sim 10^6$ electrons ($\alpha \cdot d \sim 15$), a total charge equivalent to 160 fC or a fast signal component of 8 fC. It is extremely difficult to detect this signal as it is below the threshold level of most RPC front-end electronics. Therefore, the truer picture of signal
generation in an RPC is that only when primary ionization is within 0.5 mm of the cathode (for a 2 mm gap RPC), a detectable RPC signal is produced and the notion that the RPC signal is a sum of multiple avalanches is incorrect [14].

3.3.3 Modes of operation

A Resistive Plate chamber can be operated in two different modes, the Avalanche mode (also called the limited proportionality mode) and theStreamer mode. As previously discussed, radiation passing through gas detectors creates primary ionization, which in the presence of strong electric fields undergoes multiplication till the subsequent formation of a Townsend Avalanche. A schematic description of the avalanche mode of operation can be found in Fig. 3.7.

![Avalanche development in an RPC detector](image)

Figure 3.7: Avalanche development in an RPC detector a) Primary ionization of gas atoms by through-going radiation culminating in a Townsend Avalanche in an electric field $E_0$ b) Avalanche dynamics starting to influence the electric field c) Owing to the large differences in mass, electron drift velocity is considerably higher than ions and the electrons and ions reach respective electrodes at different times. d) When ions finally reach the cathode, the discharge affects a small area of the electrodes due to its high resistivity, around the region of avalanche development [8].

Following the discussion in the previous section, the number of avalanche electrons(n) produced within the gas is given in Eq. 3.3. The equation is slightly modified, if the attachment
of electrons in the gas during their drifting motion in the presence of electronegative gases is considered.

\[ n(x) = n_0e^{(\alpha - \beta)x} = n_0e^{nx} \]  \hspace{1cm} (3.5)

where \( \beta \) is the absorption co-efficient and \( \eta (= \alpha - \beta) \) is the effective Townsend co-efficient. The amplification factor (gain) of the detector is defined as

\[ M = \frac{n}{n_0} = e^{nx} \]  \hspace{1cm} (3.6)

The factor \( M \) is distinctly different for the two modes of operation. An important aspect of the avalanche mode of operation is to avoid secondary ionisations and thus prevent streamers, necessitating detector operation with \( M < 10^8 \). The avalanche to streamer transtion occurs beyond the phenomenological Raether limit [26], when the number of electrons exceeds \( 10^8 \). Eqn. 3.6 suggests that this upper limit on the amplification factor, puts a limiting condition on the value of \( \alpha \). \( d \sim 20 \) (for the simplest case, assuming \( \beta=0 \)). Keeping in mind the statistical fluctuations involved in the electron energy distribution and correspondingly on the value of the detector gain (M), avalanche mode of operation requires an average gain \( \sim 10^6 \).

At higher values of the detector gain, there is a significant contribution from photons towards avalanche development leading to the evolution of a streamer. The Streamer mode operation of the detector is at \( M > 10^8 \) and is shown schematically in Fig 3.8.

In accordance with Pestov, a planar detector like the RPC, with resistive electrodes can be represented as a collection of discharge cells, which to a first order of approximation, behave independently [6]. A planar capacitor of area \( S \), gap thickness \( d \) and permittivity \( \epsilon \) has a capacitance (C):

\[ C = \frac{\epsilon S}{d} \]  \hspace{1cm} (3.7)
Figure 3.8: Development of a streamer in an RPC a) A Townsend avalanche developing after the passage of radiation b) At such high values of gas gain, enormous charge in the sensitive volume of the detector modifies the external electric field strongly. Photons also play a major role in spreading the avalanche and streamer evolution c) Formation of a conductive channel between the electrodes leads to sparks and discharge of wider regions of the electrodes d) The discharge causes a reduction of the electric field at the avalanche spot creating a dead area [8].

The area of the cell and the average total charge (Q) created in the gap are related as

\[ S = \frac{Qd}{\varepsilon V} \]  

(3.8)

In the avalanche mode, due to the lower gains, the signal pulse is smaller, and the average total charge \( \sim 1 \) pC. Whereas in the streamer mode, the high detector gain produces large average total charge \( \sim 100 \) pC [5][6]. The value of total charge is directly proportional to the surface area of the discharge cells as seen from Eqn. 3.8. Smaller values of Q in case of the avalanche mode, affect smaller regions of the electrodes and hence ensure better rate capability (\( \sim \) kHz/cm\(^2\)) compared to the streamer mode (\( \sim \) a few hundred Hz/cm\(^2\)) [8].

The large signal amplitude in case of the streamer mode is advantageous in the sense there is no need of amplification and signal readout is easy. The avalanche mode of operation requires sophisticated low-noise electronics owing to the smallness of the signal pulses.
3.3.4 The advent of the Multi-gap RPC (MRPC)

The basis of a gas detector having excellent timing resolution is the creation of fast detectable signals due to rapid avalanche growth. This ideally means operation at a high gas gain to ensure fast signal production. At such high electric fields, in order to prevent the rapid growth of avalanches in the gas gap and their transition into streamers, there needs to be some kind of protective mechanism to inhibit the transition and safeguard the detector. The addition of resistive plates to subdivide the gaps is the best possible solution. This multigap system not only provides necessary boundaries through the intermediate plates to prevent avalanche growth, the high resistivity of the plates ensures transparency to the detector signals induced on external metallic pickup plates. Movement of charges in any of the sub-gaps induces a signal [14]. As has already been discussed, generation of detectable avalanches requires primary ionisation closest to the cathode [28]. The variation in the initial primary ionization cluster position is what defines detector time resolution. The subdivision of the gas gap substantially reduces the time jitter and improves detector time resolution [27]. The Multi-gap design achieves a longer efficiency plateau and higher rate capabilities [28]. The schematic in Fig. 3.9 illustrates how the single gap is subdivided into multiple smaller gaps by the introduction of resistive plates, a design named as the Multi-gap Resistive Plate Chamber (MRPC).

Fig 3.9 shows the schematic of a 5-gap MRPC comprising 6 electrically floating equi-spaced resistive plates. The two outermost electrodes are graphite-painted for the application of the high voltage. Similar to the single gap design, the read-out strips located on the external surfaces of the outermost electrodes are isolated via an insulating material like Mylar. The internal plates initially assume correct voltages electrostatically upon the application of the high voltage. The plates are maintained at the right voltages by a feedback mechanism - flow of electrons and ions in opposite directions - that takes effect within the gas gap, establishing exact gain in all sub-gaps. The rate of avalanche formation being equally probable in each identical gap with an identical electric field, the passage of electrons on a side of the resistive plate is counterbalanced by the passage of positive ions on the other side of the same plate. Hence, the net passage of
charge at a given time on any of the internal electrodes is zero. Any accidental deviation of voltage on the plates (from the set value) changes the electric field of the adjacent gaps. The change in the gas gain of the adjacent gaps modifies the electron and ion flow in a way so as to neutralize the voltage change via the feedback mechanism.

As per the calculations shown in [29], the timing resolution \( \sigma_t \) of an RPC is defined as

\[
\sigma_t = \frac{1.28}{(\alpha - \beta)v_d}
\]  \hspace{1cm} (3.9)

where, \( \alpha \), \( \beta \) and \( v_d \) are the Townsend co-efficient, attachment co-efficient and electron drift velocity respectively. For the specific case of smaller gas gaps, in order to be able to create detectable avalanches, the value of \( (\alpha - \beta) \) should be higher and the higher electric field across the smaller gap would naturally mean higher electron drift velocity. Therefore, the improvement of timing resolution in case of an MRPC with smaller gas gaps is fairly straightforward from
Eqn. 3.9. In case of single gap RPC’s, gap width precision is extremely critical, otherwise, there is a large variation in detector gain. Gas gap tolerance should ideally then be even more critical in case of MRPC’s with gaps as small as \( \sim 250\mu m \). Moreover, the large charge generated within the gaps in case of MRPC’s, should see a rise in current flow through the resistive plates culminating in rate effects. Contrary to this belief, MRPC’s do not experience undue rate effects. The principal reason behind this is the space charge effect in the gap [14]. During the progression of an avalanche, as already shown in Fig. 3.5, the positive ions lagging behind at the tail of the avalanche, shield the electrons at the head from the electric field due to the applied high voltage. This reduction in electric field decreases the gas gain and limits further avalanche growth. Particularly in case of smaller gas gaps, the compactness of the avalanche, makes space charge the dominating effect and prevents the avalanche to streamer transition by limiting the number of avalanche electrons to \( \sim 10^7 \). Simulation studies done by Lippmann and Riegler discuss at length about space charge effects [30][31]. So now, imperfections in the gas gap could either lead to an increase in the electric field or otherwise. Increase in the electric field strength causes faster avalanche growth until the onset of space charge effects within the gap restricts avalanche growth. As the number of electrons in the avalanche are maintained below the Raether limit, a transition into the streamer region is prohibited and rate capability of the detector is unaffected. If the electric field somehow decreases in a certain region of the gap, the field-dependent Townsend co-efficient \( (\alpha) \) increases and the attachment co-efficient \( (\beta) \) decreases with it. As a consequence, the number of ions inside the gap increases (both positive and negative) and this excess charge should lead to increase in the currents flowing through the plates and a greater voltage drop across the plates. This should automatically reduce the detector rate, however, as has been shown in [32], a recombination of the positive and negative ions in the small MRPC gas gaps fails to cause any additional voltage drop across the plates and leaves the rate capability of the detector unaffected.
3.3.5 Applications of Resistive Plate Chambers - single gap and multi-gap

The Resistive Plate Chambers are being extensively used now-a-days as a detector for high energy physics experiments. The reasons are as follows:-

- RPC’s are built from simple, low cost materials, readily available (e.g glass and bakelite) in the market.

- Fabrication and operation of these detectors is fairly simple and the fabrication cost per unit area is quite low, compared to other detectors offering similar performances.

- Read-out of detector signals alongwith obtaining a two-dimensional readout (x- and y- from the same chamber) is relatively simple.

- Coverage of large areas, high detection efficiency (>90%) and long-term stability.

- Excellent timing resolution (~2 ns for single gap and ~50 ps for multi-gap), particle tracking capability and good position resolution.

The mode of operation of an RPC is application-specific. In the streamer mode, especially suited for triggering purposes, RPC’s are operated at ~40-50 kV/cm electric fields, efficiencies >95% and timing resolution ($\sigma$) ~1 ns. The signal readout is simple due to the absence of signal amplification requirements, however, rate capability is limited to ~100 Hz/cm². The experiments utilising RPC’s operated in the streamer mode are L3 [34], BABAR [35], BELLE [36], muon-arm of ALICE [37], BESIII [38], OPERA [39], ARGO-YBJ [40]. The upcoming Indian Neutrino Observatory (INO) [50] experiment and the DUNE experiment at Fermilab plan to use 2 mm gap Bakelite RPC’s operated in the streamer mode.

The Avalanche mode of operation demands sophisticated electronics as the charge generated in the gap is low, giving small signals that require pre-amplification. The rate capability is much higher (~a few kHz/cm²) and Multigap RPC’s operated in the avalanche mode have excellent timing resolution. As a trigger detector, avalanche mode RPC’s are used by the ATLAS [41],
CMS [42] and LHCb [43] experiments as the muon trigger detector. The PHENIX experiment uses a double-gap Bakelite RPC [44] in the avalanche mode as muon trigger. Multigap RPC’s for timing purposes are used in the HARP[45], ALICE (TOF)[46], STAR(TOF and MTD)[44], FOPI [48] and HADES [49] experiments. An excellent summary of RPC application at the different experiments worldwide can be found in Ref. [6], including mode of operation, acceptance area, electrode, gap thickness and number of gaps.

3.4 Fabrication of 5-gap Glass MRPC modules at VECC for the STAR-MTD

A large part of this thesis work is the development of glass MRPC’s for the STAR Muon Telescope Detector upgrade at RHIC. The physics motivation behind the MTD has been thoroughly discussed in previous sections. In this section, we shall discuss about detector geometry and the fabrication and testing of the five-gap MRPC’s installed at STAR. After several years of R&D with prototype detectors, starting from the year 2007, the working MRPC module design was finalised in 2011. The three types of MRPC prototypes that have been studied are:

- **Type A** - Double stack MRPC module with 10 gas gaps. Detector active area is 87 cm × 17 cm. 6 double-ended readout pads of width 2.5 cm with a 0.4 cm gap between each pad.

- **Type B** - Single stack MRPC module with 5 gas gaps. Detector active area is 87 cm × 52 cm. 12 double-ended readout pads of width 3.8 cm with a 0.6 cm gap between each pad.

- **Type C** - Single stack MRPC module with 6 gas gaps. Detector active area and readout strips identical to Type B.

The Type B MRPC prototype was chosen as the final design and the number of gaps and the read-out strip size was chosen after duly considering High Voltage constraints and the requirement of the number of electronics channels. A total of 122, single stack, 5 gap MRPC modules
of dimensions 91.5 cm × 58 cm have been installed at mid-rapidity at STAR. A schematic of the MRPC is shown in Fig. 3.10.

Figure 3.10: A schematic diagram of the Type B MRPC. The different components used for detector fabrication have been highlighted in different colors. Honeycomb boards are in yellow, Read-out strips are in red, Printed Circuit Boards (PCB) are shown in green, the Mylar insulating foil is colored light yellow while the glass plates are sky blue in color. Diagram not to scale. The vertical dimension has been enhanced to get a clear view [51].

The detectors have double-ended differential strip readout, with each strip having a dimension of 87 cm × 3.8 cm and 12 such strips on both sides of each detector. The strips are separated by a gap of 6 mm. Two different sets of float glass plates of resistivity \(~10^{13} \Omega \text{cm}\) are used for detector fabrication. The inner glass electrodes are 0.7 mm in thickness, while the outer graphite-coated electrodes for high voltage application are slightly thicker at 1.1 mm. The HV electrode is painted with colloidal graphite and a surface resistivity of \(~5 \text{ M}\Omega/\square\) is maintained to ensure electric field uniformity.

The fabrication procedure of the long MRPC modules is a non-trivial process that follows several rigorous steps, undertaken with great care and caution. The flowchart in Fig. 3.11 summarizes the MTD-MRPC fabrication procedure at VECC followed by brief outlines of the steps and pictures of the fabrication steps.

The glass plates (both inner and outer electrodes) for detector fabrication were sent to VECC by Tsinghua University, Beijing, China, along with the nylon monofilament fishing line for defining the gas gaps. This was done to ensure uniformity in the MTD-MRPC modules fabricated at the two Chinese Institutes, USTC and Tsinghua and at VECC. The inner glass plates of 700 \(\mu\text{m}\) thickness are cleaned with distilled water and Alcohol (2-propanol) to remove
Figure 3.11: A flowchart summarising the fabrication procedure of the MTD-MRPC modules at VECC.
dust from the surfaces. Four such glass plates are thoroughly cleaned for the 5-gap MRPC. The clear side of the two graphite electrodes (1.1 mm thick glass plates) are cleaned in a similar fashion.

![Printed Circuit Board (PCB) with metallic (Cu) readout strips.](image)

Figure 3.12: Printed Circuit Board (PCB) with metallic (Cu) readout strips.

The top and bottom printed circuit boards (PCB) shown in Fig. 3.12 are then cleaned thoroughly with Alcohol. The same is done for the top and bottom Honeycomb boards that provide support to the glass MRPC's.

After thorough cleaning of the boards, a double-sided tape is pasted on them carefully (Fig. 3.13).

Thereafter, the PCB’s, top and bottom, are pasted on top of the taped sides of the corresponding honeycomb boards as shown in Fig. 3.14, with adequate weights to ensure uniform adherence of the PCB’s on the boards.

The copper strips on the PCB’s are now cleaned and a mylar sheet cut to appropriate dimensions is placed on the PCB. Initially, a small part at the edge of the mylar sheet as illustrated in Fig. 3.15, used to be removed to make space for putting a graphite tape on top of the copper tape placed on the PCB.

Test results revealed that this large gap caused serious problems in the MRPC modules and arcing at the edge of the glass electrodes due to a lack of insulation. The mylar design was modified thereafter and a small rectangular opening on top of the copper strip was made to
account for the graphite tape. This new design has been illustrated in Fig. 3.16.

The graphite-coated electrode is carefully placed on top of the PCB, shown in Fig. 3.17, with the mylar foil placed on top, ensuring proper contact between the electrode and the underlying graphite tape for the uniformity of the applied high voltage. It is then cleaned with an air
gun to remove dust particles. The PCB is lined with holes on all four sides for the insertion of custom-made nylon screws and polycarbonate side spacers to hold the fishing line in position. The nylon screws and the polycarbonate spacers are placed on the PCB as shown in Fig. 3.18.

With the graphite electrode in position over the honeycomb boards the gas gaps are defined using the 250 $\mu$m nylon monofilament fishing line.

A picture of the first gas gap defined on the outermost electrode is shown in Fig. 3.19. The glass surface with the fishing line is duly cleaned with an air gun to remove any unwanted dust particles everytime, before placing new glass plates on top. This process is repeated for the four inner glass plates to define the five 250 $\mu$m gas gaps for the five-gap MRPC. During the winding
process, the fishing line is cleaned with lint-free tissue to remove dust particles from it. Fig. 3.20 shows a close-up view of the 5 MRPC gas gaps, held in place by the nylon screw to which the fishing line are wound.

The final step is to carefully place the other graphite electrode mounted on the honeycomb board with the PCB and the mylar sheet over the top of the stack of glass plates with the fishing
Figure 3.19: 250 μm nylon monofilament fishing line defining one of the gas gaps on a glass plate.

Figure 3.20: A Nylon screw holding the fishing lines in position for the 5 gas gaps. The picture shows all the components in place, from the bottom honeycomb board and PCB and the (outer and inner) glass plates, to the nylon screw and the fishing line.

lines and bolt the screws for compactness. A completed module is shown in Fig 3.21, with 4 ribbon cables connected to the strips for signal readout. The ribbon cables, also called pigtailed,
have been sent to VECC by UT, Austin, USA and have been connected conforming to the norms for the MRPC. The cables P1 and P3 are identical and are meant for strips 1-6, while the other set of identical cables, P2 and P4 connect strips 7-12.

Figure 3.22: The module is placed in the ingeniously built, gas-tight Aluminium box for testing.
The completed module is then placed in a gas-tight Aluminium box for testing as shown in Fig. 3.22. The module is then tested in the Avalanche mode with a gas-mixture of Freon (R134A) and isobutane (i-C$_4$H$_{10}$) in a volume ratio of 95 : 5 and a picture of the gas mixing and distribution system has been shown in Fig. 3.23. The High Voltage was applied with a CAEN N1470 NIM HV power supply. The detector was normally ramped up at $\sim$ 8 V/s. A summary of the components including their dimensions used during the fabrication of individual MRPC modules is shown in Fig. 3.24.

Figure 3.23: Gas mixing and distribution system.
<table>
<thead>
<tr>
<th>Material</th>
<th>Dimension (mm)</th>
<th>Tolerance (mm)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer glass</td>
<td>890×559×1.1</td>
<td>±0.5, ±0.5, ±0.02</td>
<td>2</td>
</tr>
<tr>
<td>Inner glass</td>
<td>870×549×0.7</td>
<td>±0.5, ±0.5, ±0.02</td>
<td>4</td>
</tr>
<tr>
<td>Graphite electrode</td>
<td>888×557×0.1</td>
<td>-0.5</td>
<td>2</td>
</tr>
<tr>
<td>Mylar film</td>
<td>895×564×0.15</td>
<td>±0.1</td>
<td>2</td>
</tr>
<tr>
<td>Honeycomb board</td>
<td>990×669×10</td>
<td>±1.0, ±1.0</td>
<td>2</td>
</tr>
<tr>
<td>PCB</td>
<td>915×580×0.9</td>
<td>±0.5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>12 strips, 30×870/strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fishing Line</td>
<td>Diameter 0.25</td>
<td>±0.005</td>
<td></td>
</tr>
<tr>
<td>Nylon screw</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Side spacer (poly carbonate)</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>HV lead</td>
<td>60 cm</td>
<td>±1</td>
<td>2</td>
</tr>
<tr>
<td>Signal lead</td>
<td>60 cm</td>
<td>±1</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 3.24: Summarising the components required for the fabrication of a MTD-MRPC module including their dimensions and respective quantities.
3.5 Test results of the MTD-MRPC modules at VECC with cosmic rays

After the completion of a module, it is kept in the Aluminum gas-tight box and flushed with gas for the next 3 days (72 hours), which ensures ~ 2 volume changes of gas in the detector at the flow rate of 20 SCCM (Standard Cubic Centimetre per Minute). After that, the high voltage was applied to the detector. The detector is initially seasoned by ramping the voltage manually with the CAEN N471A NIM HV power supply. It is then ramped up to the operating voltage of ±6300 Volts at the rate of 8 V/s with the CAEN N1470. The detector V-I characteristic is measured to determine the performance of the detector and is shown in Fig. 3.25.

![V-I characteristic of VECC MTD-MRPC module #9 as a function of high voltage.](image)

Figure 3.25: V-I characteristic of VECC MTD-MRPC module #9 as a function of high voltage.

The V-I characteristic curve clearly has two distinct slopes, which is an inherent feature of the RPC gas gap. The RPC gas gap can be suitably described by an equivalent circuit diagram shown in Fig. 3.26. It can be represented as a combination of the spacer resistance and the gap resistance, acting in parallel. While the behaviour of the spacer is Ohmic, the gas gap behaves like a Zener diode. The electric field at lower operating voltages is insufficient for avalanche development. Therefore, the gas gap behaves like an insulator and offers a path of infinite
resistance to the flow of current. As explained by Eqs 3.10-3.12, the slope of the V-I curve in this regime is determined by the resistance of the spacer. At higher voltages, the breakdown of the gas inside the detector changes the scenario. The development of Avalanches means the gas gap starts behaving like a conductor and offers a zero resistance path to the flow of current. The slope of the V-I curve in this regime of operation is determined by the resistance of the glass plates as shown in Eqs 3.13-3.14.

\[ R_{\text{gap}} \approx \infty \]  

(3.10)

\[ R_{\text{spacer}} \gg R_{\text{glass}} \]  

(3.11)

\[ \frac{dV}{dI} = R_{\text{spacer}} \]  

(3.12)
while at higher operating voltages:

\[ R_{gasgap} \approx 0 \]  \hspace{1cm} (3.13)

\[ \frac{dV}{dI} = R_{glass} \]  \hspace{1cm} (3.14)

A schematic of the cosmic ray test-setup is shown in Fig. 3.27. The 2 paddle scintillators \( S1 \) and \( S2 \) are of dimensions 20 cm \( \times \) 8.5 cm, while the narrow paddle, referred as the finger scintillator \( FS \) is 5 cm \( \times \) 1.5 cm. The analog scintillator and detector pulses are sent to the CAEN N841 Leading Edge Discriminator. The master trigger is determined by the 3-fold coincidence of the scintillators.

![Schematic diagram of cosmic ray test-setup for MRPC test.](image)

Figure 3.27: A schematic diagram showing the cosmic ray trigger scheme for the MRPC test.

The coincidence of the MRPC logic signal with the 3-fold is defined as the 4-fold. The CAEN N455 module is the coincidence unit used for the tests. The efficiency of the detector is defined as the ratio of the 4-fold count to the 3-fold count for a fixed time. The 4-fold and 3-fold numbers are counted using the CAEN N1145 counter module. The efficiency of the detector as
a function of the applied high voltage is shown in Fig. 3.28. An efficiency of 90% is obtained at the detector operating voltage of ±6300 Volts. The onset of the plateau region as seen from the efficiency plot (Fig. 3.28) (~12 kV) that coincides with the start of the breakdown region as seen from the V-I characteristic plot (Fig. 3.25).

![Graph showing efficiency as a function of high voltage.](image1)

Figure 3.28: Efficiency of VECC MTD-MRPC module #9 as a function of high voltage.

![Graph showing strip-by-strip noise rate variation.](image2)

Figure 3.29: Strip-by-strip noise rate variation of the VECC MTD-MRPC module #9 at the operating voltage of ±6300 Volts.
The strip-by-strip variation of the detector noise rate (normalized by strip area) as shown in Fig. 3.29 has been measured at the detector operating voltage of ±6300 Volts. The detector read-out being double sided, there are 24 readings for the 12 readout strips. As an example, 1 and 13 are opposite sides of the same strip and so on. The slightly higher noise rate for the strips at the edge is expected due to the electric field deformation at the edges. Apart from one end of strip 5 which is noisy, the rest of the strips show consistent noise rates ≈ 0.8 Hz/cm². The test results shown here are for the VECC MTD-MRPC module #9. The test results for the other 9 MRPC modules fabricated at VECC were similar. The VECC MRPC module #9 was also tested at University of Texas at Austin, USA and the test results have been shown in Fig. 3.30 and Fig. 3.31. A strip-by-strip noise rate measurement at UT Austin for module #9 is shown in Fig. 3.30 and results obtained are similar to the test results at VECC. The strips at the edges of the detector are noisy due to the electric field deformation. The pick-up strips are readout at both ends and High Z and Low Z indicate the positioning along the z axis. Fig. 3.31 shows a correlation plot of the noise measurements at the two ends of each strip. This test is performed to investigate the proper functioning of the readout channels without any damage. The 12 double-ended strips are numbered 0-11 on one side and 12-23 on the other side by convention. In the ideal case, the noise rate peaks obtained from the two ends of each strip should be mirror images of each other. Fig. 3.31 reveals identical noise rate measurements from opposite ends of each strip and that all readout strips function properly.

3.6 Cosmic ray Test results of the MTD-MRPC modules at STAR

A cosmic-ray event in STAR [51] is schematically depicted in Fig. 3.32 and passes through the MTD, BEMC, TOF and TPC detectors in the order of sequence. During the passage of a cosmic ray muon, the time recorded by an MTD-MRPC is called tMTD, while the times noted by two TOF MRPC’s on either side of the interaction point are called tTOF1 and tTOF2 respectively.
Figure 3.30: Strip-by-strip noise rate measurement of the VECC MTD-MRPC module #9 at the operating voltage of ±6300 Volts at UT Austin.

Figure 3.31: A correlation plot showing the noise correlation of the VECC MTD-MRPC module #9 at the operating voltage of ±6300 Volts at UT Austin.

The time-of-flight between the two TOF detectors can be calculated using the path length of the cosmic ray and the momentum p measured by the TPC and is referred as tTPC. Similarly, the time-of-flight through the magnet backlegs between the MTD and the first TOF detector can also be calculated using the helical path length traversed by the cosmic muon of momentum
This time is referred as tSteel.

Figure 3.32: Schematic representation of a cosmic ray event at STAR [51]

The spatial resolution of the MTD-MRPC detectors along the z direction (direction along the strips) and the azimuthal direction (direction perpendicular to the strips) are measured by extrapolating the reconstructed tracks from the TPC to the MTD. The hit position at the MTD in the Z direction is calculated as the difference between the leading times of the signal from the two ends of the readout strip that is fired. Whereas, the middle point of the strip that has the largest signal gives the φ position [51]. The $ΔZ$ and $Δφ$ distributions as shown in Fig. 3.33 are obtained as the difference between the extrapolated TPC track hit position and the measured MTD hit position in the Z and φ directions respectively. The standard deviation of the Gaussian fit to the $ΔZ$ and $Δφ$ distributions gives a detector spatial resolution of 2.6 cm and 0.006 radians respectively [51].

The time resolution of the detector is measured with tracks matching the selection criteria of $ΔZ<6$ cm and $Δφ<0.2$ radian. The timing resolution of the MTD system is obtained from tMTD after subtracting the start time contribution of the TOF detectors and the time-of-flight through the steel backlegs. The resultant expression $ΔT = (tTOF2 - tTPC + tTOF1)/2 - tMTD$
Figure 3.33: The ΔZ distribution shown in the left panel and the Δφ distribution show in the right panel. The standard deviation of the Gaussian fits (solid curves) gives the detector spatial resolution [51].

- tSteel, is plotted for each individual strip and the standard deviation of the Gaussian fit to this distribution gives the detector time resolution. The top frame of Fig. 3.34 shows the standard deviations of the ΔT distribution of each strip after correcting for slewing and offsets [51]. The bottom frame of Fig. 3.34 shows the overall timing resolution of the detector by combining the values of each strip. The standard deviation of the Gaussian fit to this distribution, 104 ps, gives the timing resolution of the detector [51].

Details of the cosmic ray test results of the MTD-MRPC modules can be found in [51]. The test results are found to conform with the expected values[52] for the MTD-MRPC’s and make this detector suitable for the physics requirements [53] that it aims to address.
3.7 Detection of 511 keV photons with MRPC’s as a proof-of-principle for TOF-PET

Among the many uses of technologies being developed for experiments on high energy physics, one of the principal spin-off benefits is the use of newer, advanced detector technologies for Medical Imaging purposes. Positron Emission Tomography (PET) is one of the many avenues that are being explored to find suitable improvements to existing detection techniques. RPC’s with excellent timing resolution, similar to the STAR-MTD MRPC’s, are being investigated as potential candidates for PET imaging [54][55]. A preliminary effort using small-sized MRPC prototypes fabricated using the same raw materials and identical detector technology as the MTD MRPC’s, has been undertaken to test the proof-of-principle of PET imaging. This has been explained in detail in the next few sections, including a discussion on the benefits of Time-of-Flight PET (TOF-PET) imaging.
3.7.1 Introduction

Positron Emission Tomography is a biomedical imaging technique in which a radionuclide labelled with a positron emitter (\(^{11}\text{C}\), \(^{13}\text{N}\), \(^{18}\text{F}\) or \(^{15}\text{O}\)) is administered into the object under investigation. The emitted positrons have an extremely small range (~1-2 mm in human tissue) and annihilate with an electron to emit two back-to-back (momentum conservation), 511 keV photons. A coincidence event is defined when a pair of photons considered from the same annihilation event are detected on opposite sides of the object being studied within a narrow time window, called the coincidence time window. The coincident detection of the two almost co-linear, 511 keV photons, is the basis of PET. It establishes the occurrence of the positron-electron annihilation event along the line joining the relevant detectors where the events were registered. This line is referred to as the Line-Of-Response, LOR. A collection of such LOR events, recorded for all possible angles, enables the reconstruction of the activity distribution of the positron emitter in the tissues. 3D tomographic images are reconstructed via filtered back-projection or by iterative reconstruction techniques [56]. There are however, several limitations as far as PET imaging and the precision of the image reconstruction is considered. Multiple factors degrade the actual achievable resolution of a PET system. The most important factors [7][57], as highlighted in Fig. 3.35 are

![Figure 3.35: Factors degrading PET resolution a) Random coincidences, b) Compton scattering of the photons c) Effect of Parallax error [57].](image-url)
• Random Coincidences: The detection of photons from different annihilation events result in random coincidences. It is a function of the detector coincidence time window for two real photons emitted from an annihilation event. Improvements in the detector time resolution help remove random coincidences.

• Compton scattering: The 511 keV photons emitted from a positron-electron annihilation event are scattered within the object being studied, during the course of their travel before detection. Compton scattering decreases the actual photon energy from 511 keV and also changes the direction of the photons. As a consequence, when a scattered event is detected, the recorded LOR has no correlation with the actual annihilation event. Such discrepancies in the data causes a degradation in the image reconstruction resolution, where the final reconstructed image is inaccurate and lacks in contrast. The sensitivity of the detection system towards photons having energy less than 511 keV plays a major role in this. Attenuation of one or both photons results in the complete loss of the actual event, causing a loss in statistics.

• Parallax Error: In crystal-based PET systems, the 511 keV photon is detected after it travels a certain distance before full energy deposition and is determined by the stopping power of the crystal. This actual location can only be truly measured if the depth of interaction (DOI) for the detector is known. The projection of this point on the surface of the detector is taken as the photon detection point and used for constructing the LOR. This causes a large parallax error if the variation between the real position and the projected point is appreciable and images reconstructed are blurred. Photons entering the detector obliquely are especially affected. Detection systems with excellent position resolution that are unaffected by parallax effects improve the resolution of the reconstructed image.
3.7.2 Advantages of Time-of-Flight in PET

The use of Time-of-Flight information in PET systems dates back to the 1980’s and a detailed summary can be found in [58][59]. Although the systems (e.g. Cesium Fluoride, CsF and Barium Fluoride, BaF$_2$ crystals) had excellent count rate, they had poor spatial resolution and could not match the sensitivity of the existing non-TOF systems (Bismuth Germanate BGO crystals). Naturally, interest in TOF-PET systems gradually declined till recently, when a resurgence in TOF-PET imaging due to the progress in scintillator technology has brought them back into use [56]. The advent of scintillating crystals with good time resolution (Lutetium Oxyorthosilicate, LSO and , Lutetium-Yttrium Oxyorthosilicate, LYSO crystals) alongwith fast, reliable PMT’s and advancements in list-mode reconstruction algorithms, make TOF usage the realistic choice. In a detection system using Time-of-Flight information, precision measurement of the arrival times of the coincident photons is possible and the difference in times helps to localize the annihilation event on the LOR [56]. Apart from reducing random coincidences, TOF information enhances the signal-to-noise ratio of the reconstructed image by minimizing noise propagation along the LOR [56] and reduces data acquisition time and dosage [57]. The annihilation position along the LOR can be established with an FWHM accuracy $\Delta L$ [54] related to the FWHM accuracy in time $\Delta t$ as shown below

$$\Delta L[mm] = c \frac{\Delta t[ps]}{2}$$ \hspace{1cm} (3.15)

$$\Delta L[mm] = c \frac{2.36 \sqrt{2} \sigma_t[ps]}{2}$$ \hspace{1cm} (3.16)

$\sigma_t$ is the rms timing resolution of the detecting element.
\[ \Delta L [\text{mm}] \approx \frac{\sigma_t [\text{ps}]}{2} \]

According to Eq. 3.17, a detector time resolution of 100 ps (rms) localizes the annihilation point to an FWHM accuracy of \(\approx 50\) mm. Although this value is well beyond image granularity (\(\sim\) a few mm) requirements [54] for PET systems, it certainly helps in terms of the image reconstruction process. A schematic diagram shown in Fig. 3.36 highlights the advantage of using TOF information in PET imaging.

Figure 3.36: a) The positron emitted by the administered radionuclide emits two coincident back-to-back 511 keV gamma rays upon annihilation with an electron. The arrival time difference of the photons \((t_2 - t_1)\) helps localize the annihilation event along the line of response (LOR) joining the two detectors X and Y. b) Event reconstruction using TOF information is done within a reduced back-projected region \((\Delta L)\) of the LOR determined by the system time resolution [56].

Utilizing TOF information on an object of diameter \(L\) being investigated, an enhancement in sensitivity of \(\sim L/\Delta L\) is achieved, thus reducing the event statistics requirement for the reproduction of images [60]. In non-TOF systems, larger objects suffer from increased attenuation that causes loss of real events and an enhancement in Compton scattered events that lead to poor image quality. TOF-PET has the ability to significantly improve image quality for larger
objects, at par with smaller objects, by accumulating higher statistics within acceptable scan times [56]. The importance of detector time resolution ($\sigma$) is paramount in case of TOF-PET systems. As shown in Eq. 3.17, the better the time resolution of the detector ($\sigma_{t}$), the smaller the extent of the back-projected LOR region for image reconstruction, hence better the image quality. The other usefulness of excellent time resolution is in minimizing the coincidence time window ($4\sigma_{t}$) [7]. A lower time window clearly reduces the number of random coincidence events. Therefore, detection systems with excellent time resolution are extremely essential for PET imaging.

### 3.7.3 Advantages of RPC’s for use in PET

As previously discussed, RPC’S are gaseous detectors being used worldwide in high energy physics, nuclear physics and neutrino experiments for charged particle detection and are known for their excellent position and timing resolution. The MRPC [28] is a variant of the RPC, conceived in the year 1996, with smaller gas gaps and a much improved timing resolution. Efforts to use the RPC as the detection system in TOF-PET can be found avidly in literature [57][61][62][63]. The potential of RPC’s as TOF-PET detection systems can be highlighted through the following:

- Detectors have naturally layered structure suited to photon conversion and are based on the converter-plate principle [64].

- Fabrication of an MRPC is simple, inexpensive and economic construction of large-sized detectors is quite feasible. The Field-Of-View attainable with RPC’s [65] comes at a much lower cost compared to existing crystal based systems [57][63]. A larger FOV reduces scan times and dosage.

- Excellent timing resolution ($\sigma$) values have been published for MRPC’s ($\sim$20 ps for charged particles [66] and $\sim$90 ps for single photons [54]).
• Excellent Position resolution values reported for RPC’s with a resolution up to ~sub-millimeter achievable [62].

• Parallax errors are absent for detection with RPC’s.

• RPC’s are unaffected by magnetic fields, hence they are compatible with Magnetic Resonance Imaging (MRI).

• The efficiency of gamma detection for RPC’s increases as a function of gamma energy as it increases from 200 keV to 500 keV. To the contrary, in case of scintillators, the efficiency goes down beyond gamma energy of 100 keV [63]. Therefore, Compton scattered photons of energies less than 511 keV are naturally suppressed for RPC’s.

To sum up, there is a stark contrast between the existing scintillator crystal-based TOF-PET imaging and the proposed MRPC-based TOF-PET imaging. However advantageous MRPC technology might seem, it has obvious limitations, especially for gamma detection as discussed in the next section. Use of MRPC’s for TOF-PET imaging seems to be the practical choice for the future and a better alternative to the existing expensive scintillator-based technology. Extensive R&D on the topic is being carried out worldwide by several groups.

3.7.4 Limitations of RPC-PET

The critical factor that determines the sensitivity of the gamma detection system for TOF-PET is the quantum efficiency of the detector. The quantum efficiency for RPC’s is defined as the number of 511 keV $\gamma$’s detected to the original number of $\gamma$’s incident on the detector. RPC’s being charged particle detectors their photon detection efficiency [54][67] is much lower in comparison to scintillating crystals [63]. The main concern with RPC’s is thus the maximization of the gamma detection efficiency which can be improved by using MRPC’s and optimising the number of glass plates to improve gamma conversion into electrons and their subsequent detection. Another parameter is the optimization of the electrode thickness as the photons primarily interact with the detector electrode material via the Compton effect.
3.7.5 Fabrication and testing of the six-gap MRPC prototype

Despite the challenges of gamma detection with MRPC’s mainly in terms of low detection efficiency, their simple and economic construction paves the way for stacking large number of MRPC detectors to increase gamma conversion. An increase in detection efficiency, along with their excellent timing resolution and position resolution can suitably make MRPC’s an alternative to the currently used highly expensive scintillator-based systems for PET. The preliminary gamma detection efficiency results of a six-gap MRPC prototype operated in avalanche mode, using a $^{22}\text{Na}$ source as the $\beta^+$ emitter has been discussed here. The MRPC prototype [68] has dimensions $16 \text{ cm} \times 10 \text{ cm}$, is built with seven float glass plates, each of thickness $600 \mu\text{m}$, obtained from GSI, Germany. The gas gap between the plates is defined by $200 \mu\text{m}$ polycarbonate buttons. The prototype is operated in the avalanche mode with a gas mixture of eco-friendly Freon (R-134A) and Iso-butane, in the ratio 95 : 5. The $^{22}\text{Na}$ source is placed between the MRPC prototype and a plastic scintillator of dimensions $5 \text{ cm} \times 1.2 \text{ cm}$ as shown in Fig. 3.37.

![Figure 3.37: Experimental Set-up for testing the prototype MRPC with the $^{22}\text{Na}$ source [69][70].](image)
3.7.6 Experimental Results with the 6-gap MRPC prototype

The positrons emitted by the source travel a very short path length (∼ 1-2 mm in human tissue [7]) before annihilating with electrons producing two almost anti-parallel 511 keV photons. The test results with the 6-gap MRPC and the plastic scintillator are performed in two different configurations, with the $^{22}$Na source and without the $^{22}$Na source placed between them. The tests without the source is referred as the non-source configuration and is performed to remove the background arising from cosmic muons. Coincidence count rate between the signals obtained from the MRPC strips and the scintillator is measured with and without the source. With the increase of the applied high voltage, the coincidence count rate increases. The coincidence count rate as a function of the applied high voltage is shown in Fig. 3.38 and it clearly establishes the effect of the source.

![Graph showing coincidence count rate vs. voltage](image)

**Figure 3.38**: The coincidence count rate as a function of the high voltage [69][70].

In the presence of the $^{22}$Na source, the ratio of the two fold coincidence count rate between the MRPC signal and scintillator signal to the number of photons counted by the scintillator (after
subtracting the background contribution due to cosmic muons from the non-source configuration) is defined as the photon-pair detection efficiency. The variation of gamma detection efficiency as a function of the high voltage is shown in Fig. 3.39. The efficiency increases with that of the high voltage and tends to saturate at higher voltages. A photon-pair detection efficiency of 0.9% is obtained at a high voltage of 15 kV after correcting for geometrical acceptance and cosmic ray effect measured in non-source configuration [70][69].

![Graph showing efficiency vs voltage](image)

Figure 3.39: The pair detection efficiency as a function of the high voltage [69][70].

In an effort to locate the $^{22}$Na source position, the distance between the scintillator and the MRPC is fixed at 44.5 cm and the time difference between the signals from the scintillator and the MRPC is measured by varying the source position. A simple mathematical calculation assuming a photon velocity of 30 cm/ns gives the expected time difference between the signals. Experimentally, the time differences at the 4 different source positions are obtained by taking the mean ($\mu$) of the Gaussian fit to the time distribution acquired with the start signal from the scintillator and the stop signal from the MRPC. The large error bars are the standard deviation ($\sigma$) values from the Gaussian fit to the time distribution. The calculated and measured time difference as a function of source distance (source distance is measured from the MRPC...
Figure 3.40: Calculated and measured time difference as a function of source distance [69][70].

The measured data (data points with error bars) and the calculated data (solid line) are shown in Fig. 3.40 [69][70]. Given the large error bars, the experimentally measured time difference values follow the trend of the calculated time difference values using a 30 cm/ns photon velocity.

### 3.7.7 Fabrication and testing of the two-MRPC coincidence system

Two identical 5-gap MRPC prototypes of dimensions 18 cm × 18 cm have been built and Fig. 3.41 shows the construction of one such prototype. The prototypes have been built with 0.7 mm glass plates used for the MTD-MRPC modules cut to prototype dimensions and the same nylon monofilament fishing line of thickness 250 μm has been used to define the gas gaps. The only difference from STAR geometry is that the outer electrodes are also of the same dimension as the inner electrodes. The electrodes were spray-painted using a semi-conducting graphite paint manufactured by Kansai Nerolac, India in a 1:1 ratio by volume with a special dry thinner from the same company. The obtained surface resistivity for the electrodes is $\sim 0.7$-$0.8 \text{ M}\Omega/\square$. A frame made of Perspex with an “O”-ring on top is used as the gas-tight box for the assembly of the glass plates. The fishing lines are wound on nylon screws inserted into the frame through
Figure 3.41: Steps of fabrication of the 18 cm × 18 cm prototype MRPC module a) The graphite coated electrode is placed on the frame made of “Perspex”. The nylon screws are placed to define the gas gaps and the provision for the application of High Voltage has also been made. b) The 250 μm fishing line is used to define the gas gap c) Four inner glass plates are subsequently stacked and the outer electrode is placed at the top d) The top part of the frame is placed and the complete gas-tight module is then flushed with gas, ready to be operated in the avalanche mode.

custom-made holes. The detector has two gas nozzles for gas throughput and wires are soldered on both sides for the application of high voltage. CAF₄ is applied at the soldering joints for insulation. The prototypes are tested in the Avalanche mode, using an identical gas mixture of Freon and Iso-butane in the ratio 95 : 5 as used for the MTD MRPC modules. This new 2-MRPC set-up has been built as an improvement of the previous work, where the plastic scintillator is being replaced by an identical MRPC, aimed at improving the overall measurement.

3.7.8 Preliminary timing resolution measurement

As shown in Fig. 3.42, a cosmic ray test-setup is made to test the timing resolution of the two MRPC prototypes. The detector time resolution is tested with a scintillator-based cosmic ray muon telescope and also in coincidence with each other. In the first case, the scintillator
Figure 3.42: The two-MRPC coincidence setup for testing the detector timing resolution.

telescope is built with 3 plastic scintillators arranged as shown in Fig. 3.42. The dimesions of the two paddle scintillators are 20 cm × 8.5 cm, while the finger scintillator is 5 cm × 1.5 cm. The detector readout is in the form of copper strips of size 2 cm with a gap of 2 mm in between. The master trigger is defined as the coincidence of the scintillator signals (3-fold or 3F) and is connected to the TDC start, while the MRPC logic signal is sent to the TDC-stop after a fixed 50 ns delay. The TDC module used for the test is a PS 7186 TDC. The data acquisition system is CAMAC-based. Fig. 3.43 shows the variation of detector time resolution as a function of the applied high voltage. A resolution ~120 ps has been obtained at the operating voltage of ±7900 Volts (15.8 kV) after subtracting scintillator contribution. All measurements have been done using a 4 channel CANBERRA 454, Constant Fraction Discriminator for digitising the analog pulses. The TOF-PET sensitivity depends heavily on detector time resolution and the excellent time resolution ~ 120 ps obtained with the new MRPC prototype is promising for future tests with the $^{22}$Na source.
Figure 3.43: Timing resolution measured with Scintillator 3-fold as TDC-Start and delayed detector logic pulse as TDC-Stop. The error bars are within marker size.

3.8 Conclusions and Outlook

The responsibility of VECC towards the STAR-MTD project of building 10% of the required modules has been successfully completed. 10 MRPC modules were tested thoroughly at VECC and then shipped to UT, Austin for further tests. There were quite a few issues with detector fabrication, but, they were sorted during the course of the process. One of the modules was shipped to USTC for further tests before being shipped to UT, Austin. The modules were tested OK. A six-gap glass MRPC tested in the avalanche mode with 511 keV photon pairs from a $^{22}$Na source showed a clear signal of photon pairs above background as detected by a scintillator and MRPC coincidence [69][70]. A preliminary effort to identify the source location using the MRPC-scintillator coincident timing distribution was successful and matched the calculated data within error bar [69][70]. A two-MRPC coincidence set-up has been built, which is expected to give better estimation of the ability of the system to detect photons from the $^{22}$Na source in coincidence, due to better detector resolution. Preliminary results indicate the time resolution of the newly fabricated 5-gap detectors to be $\sim 120$ ps at the operating voltage of 15.8 kV, while tests with the source are currently ongoing.
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