Chapter 1

Introduction

The elementary particle called “Neutrino” was first proposed by Wolfgang Pauli in 1930, to explain the continuous energy spectrum in beta decay. It was found in an experiment by Clyde Cowan and Frederick Reines in 1956 (Reines got the Nobel prize in physics for this work in 1995). Ever since then the research activity in this area has grown especially so in the last 15 years. This was facilitated by very important developments in particle detectors and associated instrumentation. The research on the neutrino studies has led to several Nobel prizes. There are large numbers of experiments being carried across the world to study the little known neutrino properties.

1.1 Introduction to Neutrino

The neutrino is tiny sub-atomic particle with zero electric charge. Neutrinos are the second most abundant particles in the universe, next to photons. They have a tiny mass $\sim 100$ m eV or about a million times smaller than an electron. In the universe there are about 300 neutrinos in every cubic centimetre. These were created during the big bang, and are also continuously produced in the Sun (about 65 billion every second passing through every square centimetre of earth), natural radioactive decays. Manmade neutrinos are produced through particle accelerators and in nuclear reactors. Neutrinos are extremely difficult to detect as they interact very weekly with matter.

There are three flavours of neutrinos and are known as electron neutrino, Muon neutrino and tau neutrino and are named after the type of particle that arises when a
neutrino undergoes a charged current interaction with a nucleus or an electron. The phenomenon of changing of flavour as it propagates is known as “Neutrino Oscillation”.

The Neutrinos were produced extensively in the Big Bang and depending on their mass, can have a significant influence on how the universe evolves. Neutrinos are an essential part of the production of all the elements heavier than the iron in collapsing stars called supernovae. The Sun, which is one of the 400 billion stars in the Milky Way galaxy, is also a strong source of neutrinos of about 60 billion per square cm per second. The neutrinos which weakly interact with matter are detected through their interactions with the nucleus or electrons. The cross section of neutrino-nucleus interaction is of the order of $10^{-42}$ cm$^2$ making it difficult, though not impossible, to detect them. The neutrinos have zero mass in the Standard Model (SM) of particle physics and do not change their type or flavour. The Super Kamiokande group and the heavy water detector at Sudbury Neutrino Observatory (SNO) have found evidence for neutrino oscillation in measurements of atmospheric neutrino and solar neutrinos, respectively. Another consequence of these experiments is that neutrinos have a non-zero mass and that they violate flavour conservation. Thus neutrinos serve as a window to study physics beyond the Standard Model.

India was a pioneer in the field of neutrino physics, conducting experiments in the underground laboratories at Kolar Gold Fields. The first reported evidence on the existence of atmospheric neutrinos, produced by cosmic rays hitting the upper atmosphere, was observed about 50 years ago in the Kolar Gold Fields at a depth of 7600 feet. In the Standard Model of particle physics neutrinos belong to the family of leptons.
Cosmic rays enter the atmosphere (upper layer) and interact with oxygen and nitrogen nuclei in the air and produce $\pi^\pm$ which decays to $\mu^\pm$ which also decays. These decays of pion and Muon generates approximately two $\nu_\mu$ (Muon neutrino) and one $\nu_e$ (electron neutrino). The cosmic ray shower is shown in Figure 1.1. The average energy of neutrino $E_{\nu} \sim$ few GeV and the neutrino flux $\Phi(\nu) \sim 10^4 \text{ m}^{-2} \text{ sec}^{-1}$.

Figure 1.1: Primary cosmic ray shower

1.2 India based Neutrino Observatory

The India-Based Neutrino Observatory (INO) [1], [2] is an upcoming mega science project to study the properties of neutrinos and is an approved project by the Government of India under the research program of the Department of Atomic Energy [3]. The plan is to build a world class underground laboratory in the Bodi hills in Tamil Nadu, India. As neutrinos are weakly interacting particles it is necessary to have large mass and shield the detector to filter out all other particles interacting which are abundant. The experimental site is shown in Figure 1.2. Collaboration has been formed consisting of various institutes which have expertise in detectors, electronics, magnets, simulations etc. The proposed INO project primarily aims to study
atmospheric neutrinos, namely to identify the mass ordering of the 3 neutrino mass 
Eigen states, in a 1,300-m deep cavern. The INO will have large magnetized iron (1.5 
Tesla) as target mass (50 k ton phase I and will be 100 k ton in phase II), good track-
ing and energy resolution (tracking calorimeter), good directionality using the fast 
timing of ~ nS time resolution and charge identification.

The active detector elements will be the Resistive Plate Chamber (RPC). In the 
phase I, the proposed ICAL detector will have 3 modules and each module will be of 
size (16 × 16 × 15 ) m³, consisting of a stack of 151 layers with ~ 5.3 cm thick iron 
plates interleaved with Resistive Plate Chamber (RPC) detector layers. The conceptu-
al design of ICAL detector is shown in Figure 1.3 and Figure 1.4 shows the RPC 
layout in the detector. In the phase I, a total of about 28,800 RPCs of dimension of 
about (2 × 2) m² will be used for this experiment and details of ICAL are summarised 
in Table 1.1. The Data Acquisition (DAQ) is a VME based system and the block dia-
gram is presented in Figure 1.5. The details of which are given in [4].

The results of one of the RPCs with continuous long term Muon tracks and image 
of an RPC with the actual Muons in a 12 layer stack of RPCs and is shown in Figure 
1.6.

INO-ICAL is an atmospheric neutrino experiment and can be used to probe phys-
ics beyond the Standard Model. The atmospheric neutrinos in the energy range of (5 
to 10) GeV is sensitive to matter effects modifying the neutrino oscillation in free 
space. As a result the ICAL experiment is sensitive to the ordering of the masses of 
the three mass states of neutrinos [5]. The other experiments in the INO cavern name-
ly study of Dark Matter and Neutrino-less Double Beta Decay, are also in the R&D 
stage and will be set up in the underground laboratories of INO.
Figure 1.2: INO ICAL site at Bhodi Hills

Figure 1.3: INO-ICAL Detector
Figure 1.4: ICAL showing RPCs one road on one side

Figure 1.5: Block design of DAQ for ICAL
Figure 1.6: Muon tracks and image of an RPC with Muons

Table 1.1: INO ICAL at a glance

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of modules</td>
<td>3</td>
</tr>
<tr>
<td>Module dimensions</td>
<td>16 m × 16 m × 14.45 m</td>
</tr>
<tr>
<td>Detector dimensions</td>
<td>48 m × 16 m × 14.45 m</td>
</tr>
<tr>
<td>No. of Layers</td>
<td>150</td>
</tr>
<tr>
<td>No. of Iron plate Layers</td>
<td>151</td>
</tr>
<tr>
<td>Iron thickness</td>
<td>5.6 cm</td>
</tr>
<tr>
<td>Gap for RPC</td>
<td>40 mm</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>~ 1.3 Tesla</td>
</tr>
<tr>
<td>RPC dimensions</td>
<td>1.845 m × 1.740 m</td>
</tr>
<tr>
<td>Read out strip width</td>
<td>3 cm</td>
</tr>
<tr>
<td>No. of RPC/Road/Layer</td>
<td>8</td>
</tr>
<tr>
<td>No. of Road/Layer/Module</td>
<td>8</td>
</tr>
<tr>
<td>No. of RPC units / Layer/Module</td>
<td>64</td>
</tr>
<tr>
<td>Total No. of RPCs</td>
<td>28,800</td>
</tr>
<tr>
<td>No. of read out channels</td>
<td>$3.7 \times 10^6$</td>
</tr>
</tbody>
</table>
The development of RPC detectors, electronics, gas systems, the required magnetic field etc. are in the final stage due to the dedicated effort by the collaborating institution and universities.

1.3 RPC (Resistive Plate Chamber)

The RPC [6], is a gaseous ionization detector for particle physics characterized by high detection efficiency (97-98%), a very good time resolution (1.5-2 ns), a good spatial resolution (~1 cm) [7] and good reliability. It’s compactness along with an industrial-supported production makes it an ideal instrument for fast response application like Muon trigger in many large experiments in involving large surface area cover [8].

1.3.1 Basic Construction of RPC

A typical view of an RPC built with a 2 mm thick float glass is shown Figure 1.7. It consists of two components, one is gas-gap and the other is signal readout panel. The gas gap of 2 mm is formed by using two glass plates having coated high resistivity on the outer surface, separated by small spacers (buttons) usually 2mm. The gas nozzles have been used to flush gas through the tiny gap. In order to apply high voltage on each plate, a resistive coating having surface resistance of about 1M ohm/square is applied [9], [10], [11], [12]. The resistance value depends on the specific application of the experiment where the RPCs are used. The tool used to measure the resistance coated on the glass is shown in Figure 1.8. The read out panels are used to collect traces of particles from gas gap, which act like transmission lines. The concept is similar to that of a capacitor.
Figure 1.7: Typical RPC with pickup panels

Figure 1.8: Zig to measures conductive surface resistance
1.3.2 Working principle of RPCs

The gaseous ionization detector consists of a gas gap bounded on both sides by two parallel electrodes made of commercially available float glass. The outer surface of the two glass plates are applied with a high voltage (about 10 kV) and the current drawn is of the order of few tens of nA depending on the size of the RPC. When a sufficiently energetic radiation passes through the chamber, it ionizes the gas molecules and produces a certain number of electron-ion pairs. The number (mean) of electron-ion pairs created is proportional to the energy deposited on the chamber. With the application of electric field, the electrons are drawn towards the anode and the ions are drawn towards the cathode and the charge gets collected. If an intense electric field is applied, further ionisations are produced by the primary electrons. The electrons produced in secondary ionisations are further accelerated to produce more ionisations and so on. This chain of ionizations causes a distribution of free charge in the gas having a characteristic shape of an avalanche. The recombination of electron-ion occurs, thus liberating photons, which can also initiate secondary ionisations. When series of several secondary avalanches are formed, a large amount of free charge is formed within the gas creating a streamer pulse. Then, these growing numbers of charges propagate within the gas inducing a signal in the read-out electrodes. The type of the gas mixture used plays a vital role in determining either the chamber is working in the avalanche regime or the streamer regime [13].

If $n_0$ primary electrons accelerated by electric field and $x$ is the distance between anode and point of interaction then no of electrons that reaches the anode ($n$) is given by equation,
\[ n = n_0 e^{\eta x} \quad (1.1) \]

where,

\[ \eta = \alpha - \beta \quad (1.2) \]

“\( \alpha \)” is first Townsend Coefficient which represents number of ionisations per unit length and \( \beta \) is attachment coefficient which represent number of electrons that are captured by gas per unit length. The gain factor \( M \) of RPC which decides the mode of operation is defined as

\[ M = \frac{n}{n_0} \quad (1.3) \]

![Working of RPC](image)

Figure 1.9: RPC showing ionisation before and after passage of charge particle

If \( M \) is greater than \( 10^8 \), the probability of streamer formation is more giving rise to streamer mode of operation of the RPC, while \( M \) less than \( 10^8 \) settles the RPC with avalanche mode of operation. The charge particle before and after passing in the detector is shown in Figure 1.9. Discharge is localized to about 0.1 mm\(^2\) area and it
takes about 2 second to recharge the dead area of detector. Thus each discharge locally deadens the glass RPC and the recovery time called dead time (τ) can be calculated as follows.

\[ \tau = RC \]

where R is the resistance of the glass plate given by \( (\rho \, \frac{1}{A}) \), C is the capacitance of the RPC given by \( (k \varepsilon_0 \, \frac{A}{d}) \)

where \( \rho = 5 \times 10^{12} \, \Omega \cdot \text{cm} \), \( l = 2 \, \text{m} \), \( A = 2 \, \text{m}^2 \), \( k = 4 \) and \( \varepsilon_0 = 8.854 \times 10^{-12} \, \text{F/m} \)

and \( d = 2 \, \text{mm} \). Then \( \tau \approx 2 \) seconds of dead time.

### 1.3.3 Types of RPCs

There are various types of RPC [14],[15],[16] and these are classified based on the material of electrode, number of inter electrode gaps and their application.

### 1.3.4 Classification of RPCs based on material of Electrode

**Bakelite RPCs:** The Resistive plates or the electrodes are made of Bakelite, coated with linseed oil from inside and with conductive coats at the outer surface. These resistances are of few Mega ohms per square. The typical gas mixture used is 95.2-96.2% of R134a \([\text{C}_2\text{H}_2\text{F}_4]\), 3.5 % to 4.5% of I-butane \((\text{C}_4\text{H}_{10})\) and 0.3% Sulphur hexafluoride \((\text{SF}_6)\), with a 45% relative humidity. The water vapour is generally added to obtain a gas mixture with a relative humidity of 40–50%, which affects the resistivity of plate material. The Bakelite based, to improve efficiency at lower operating voltage and thus, avoid a degradation of RPC performance under high background conditions [17],[18] and [19].
**Glass RPCs**: The electrodes are made of float glass of typical thickness of 2 mm or 3 mm, coated with conductive coating at the outer surface with resistance of few Mega ohms per square. The gas volume is of 2 mm, with higher bulk resistivity and better time resolution than Bakelite. The mechanical stiffness and surface quality of glass electrode are superior to Bakelite [20]. Due to delicacy of glass, handling needs proper tools.

**Hybrid RPCs**: Combination of metallic and resistive electrodes is used to make hybrid RPCs. Precaution needs to be taken to avoid gas-gap confinement by metal-metal electrodes otherwise it will be “Parallel Plate Chamber (PPC) and will have violent discharge [21].

### 1.3.5 Classification of RPCs based on number of gas-gaps

**Single gap RPC**: It is basic original form of RPC which contains one gap formed with 2 electrodes. Usually the gap is 2 mm, so the required high voltage for operation will be under limit (about 10 KV). The current drawn is few nA.

**Double gap RPC**: It has two gaps. Double gap RPCs designed with larger number of electrode and read-out panels allows more variety in structures of RPCs. It improves the timing of detector.

**Multi-gap RPCs**: These RPCs are introduced in year 1996 [22]. The most important feature of this design is inclusion of resistive plates electrically (floating electrodes) that divide the gas volume in to a number of individual gas gaps without the need of any conductive electrodes. It has time resolution about pS, but it requires higher voltage for operation.
1.3.6 Classification based on mode of operation

The RPCs can be operated in two modes namely the avalanche mode and the streamer mode, that differ in the mechanism in which signal is generated [23].

a.) **Avalanche mode:** The charged particles that are accelerated by the electric field, produces primary ions, which again produces secondary ionizations by collision with gas molecules. The electric field of this cluster of ionized particles is opposed by the external field and the multiplication process stops after sometime. These charges are then drifting towards the plates where from they are collected. The avalanche mode operates at a lower voltage and has less gain. Typical pulse amplitudes are of the order of few mV. In this mode, the RPCs Gain Factor \((M)\) is below \(10^8\) and the secondary ionization is controlled by suitable gas mixture.

b.) **Streamer mode:** Here the secondary ionization continues to occur until there is a breakdown of the gas and a continuous discharge takes place as shown in Figure 1.10. This mode operates at a higher voltage and also results in high gain. Typical pulse amplitudes are of the order of 100-200 mV. As a result of secondary ionisation, the gain Factor \((M)\) is more than \(10^8\) which gives streamer Pulses. The amplifier may not be needed for further processing the pulse information [24].
The desired mode of operation decides the gas mixture inside an RPC. Originally the RPCs were operated in the streamer mode using Argon gas based mixture, the higher signal of few 100 pC (few tens of millivolt pulse) with high current. The streamer mode has poor rate capability of about 100 Hz/cm².

The avalanche mode uses Freon based mixture of gas, the signal is low with few pC (few millivolts) and low current of few nA. It also has high voltage drop at high particle rate so is useful in good rate capabilities (few kilo hertz’s per centimetre square). The detector has aging issues in streamer mode and high counting rate (by an order of magnitude) applications has made avalanche mode popular than the streamer mode. It is possible to suppress the streamer formation by using quenching C₂F₄H₂ based gas mixtures with small quantity of SF₆. The broad comparison of Avalanche and Streamer mode is given in Table 1.2.
The transitions from the avalanche to streamer in RPCs is studied in detail and documented by R.Cardarelli, R.Santonico et al [19]. The study was based on the direct inspection of the signal produced by the RPC. The data shows that the avalanche amplitude to be strongly dependent on the operating voltage value where the saturation occurs and streamer starts and the streamer is accompanied by a precursor pulse and according to their studies the high voltage must cause the variation of the streamer time position in two times more than in the avalanche case etc.

The measurements of avalanche size and position resolution with different resistance, avalanche to streamer transition etc. is given in [25],[26], [27] etc.

1.3.7 Timing RPCs

The timing RPCs were developed in late 1990’s and have currently have reached a resolution of (50 to 60) picoseconds for an electrode areas ranging from about (10 to 1600) cm². The initial current grows exponentially in time, until the discriminating
level is reached. The delay in time is independent from the position occupied by the initial charges in the gap, providing excellent timing [13]. The timing jitter depends on the variation of the initial current (avalanche and cluster statistics) and inversely on the current growth rate is \((a \times v)\), where \(a\) is the First Townsend Coefficient and \(v\) is the electron drift velocity. The combination of metallic and resistive electrodes with signal-transparent semi-conductive layers, highly isolating layers and different kinds of pickup electrodes makes the RPCs with a rich variety of configurations, tuneable to a variety of requirements.

1.3.8 Trigger RPCs

In the Accelerator based experiment (CMS, ATLAS), several type of detectors (RPC, DFT, Scintillator based etc.) are employed and operation in the experiments. RPCs have an advantage of good time resolution and hence are used for triggering the events, based on certain criteria (which will also provide information on the presence and arrival time of charged particles). The RPCs used in ATLAS section of LHC are triggering RPCs and usage details are given in [21], [28], [29].

1.4 ICAL RPCs

The proposed INO-ICAL detector will be instrumented with 28,800 single gap RPCs. These RPCs are of \((1.85 \times 1.9)\) m\(^2\) size, consists of two glass electrodes separated by 2 mm and use a gas mixture composition of R134a \((C_2H_2F_4)\), I-butane \((iC_4H_{10})\) and sulphur hexafluoride \((SF_6)\) in the ratio of 95.4 %, 4.5% and 0.1% respectively and are operated in avalanche mode. As the numbers of RPCs are large, the total gas required is of the order of about 200 m\(^3\) and hence it is mandatory to use a Closed Loop Gas mixing System (CLS) to supply the gas into the detectors into reuse
the gas coming out of the RPCs. The ICAL detailed gas requirement is shown in the Table 1.3.

Table 1.3: INO ICAL Gas requirement

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Gas Channels/Road/Layer</td>
<td>2</td>
</tr>
<tr>
<td>No of Gas Channels/Layer/Module</td>
<td>16</td>
</tr>
<tr>
<td>No of Gas Channels/Module</td>
<td>2416</td>
</tr>
<tr>
<td>Total No. of Gas Channels</td>
<td>7248</td>
</tr>
<tr>
<td>Gas Volume /RPC/Layer</td>
<td>7.03 litre</td>
</tr>
<tr>
<td>Gas Volume /Layer</td>
<td>450 litre</td>
</tr>
<tr>
<td>Gas Volume/Module</td>
<td>67,500 litre</td>
</tr>
<tr>
<td>Total Gas Volume</td>
<td>2,02,500 litre</td>
</tr>
</tbody>
</table>

Each of these detectors will have 64 readout channels on X-side and similar number on the Y-side. Therefore, there will be about 3.7 million channels to be read and processed, based on criteria of trigger for neutrino studies. The RPC is a gaseous detector and its performance dependence on the quality of the gases and more over the number of these detectors are huge and considering the safety aspects, an automated CLS that will supply mixed gas and purify it after flowing through the RPC in a loop is designed, developed and is in operation for the last 5 years. The details of which are described latter.

The ICAL magnet provides target nucleons for neutrino interaction as well as it serves a medium in which secondary charge particles can be separated on the bases of their magnetic rigidity so that their momenta can be estimated. The magnetized iron calorimeter will use iron of low carbon iron (less than 0.1%) in order to have good magnetic characteristics and uniform magnetic field.
The INO ICAL design is modular so that future up-gradation is feasible and the detector readout system will have a time resolution of 1 nS and special resolution of about a 1 cm.

1.4.1 Brief construction of ICAL RPCs

INO RPCs use simple float glass as electrode having thickness of 3 mm, and area of about (2 × 2) m² in size with two big chamfering at two diagonally opposite corners (for electronics boards) and small chamfer at the other two corners. Usually cleaning of cut glasses is done with high purity ethyl alcohol solution and distilled water. Cleanliness is very important factor during fabrication which enhances performance of the operation of RPC. One surface of each glass is coated with conductive paint.

Two methods of painting to get the required resistance on the glass surface are achieved, namely the spray painting and the screen printing. The glass surface is coated with a mask of 10mm around the edges.

In case of spray painting a special conductive paint has been developed by M/s Nerolac Kansai Paint (India) Limited [30]. This paint uses 50% of slow drying thinner and the expected Wet Film Thickness of about 20µ. The second method is by screen printing using screen printing ink or called as carbon paste namely DC20 and DC1000M (which are 20 ohm and 1000 mega ohm pastes respectively) of Dozen make in the ratio of 1:5.5 used to achieve the required resistance of 1MΩ per square of surface resistance. The coated glasses are then cured at temperature of about 80-100 degree Celsius for few minutes. Two coated glasses are then used to form a “glass gas gap” (air leak tight), which will have electrodes that are separated by 72 polycarbonate buttons with a spacing of 20 mm and to maintain 2 mm gap over large area. Side spacers, big and small chamfers are used to seal the chambers. Four gas nozzles are used for gas inlet and outlet. The Epoxy of 3M make (DP190-grey) is used for
gluing chambers. After leak test, these gaps are made available for assembly of RPC. The detailed poly carbonate components used to fabricate an RPC are shown in Figure 1.11.

![Figure 1.11: Polycarbonate components of a glass RPC](image)

1.4.2 V-I characteristics of RPCs

A V-I characteristics study for a typical RPC is plotted and shown in Figure 1.12. It has been done to find Ohmic and discharge region of operation of this RPCs. The voltage is gradually increased and corresponding leakage current is noted down. The V-I shows that at lower voltage contribution due to leakage current through spacers is more. As the high voltages increases the gas volume contributes more in leakage current. It takes about (5 to 6) days to stabilise the current drawn by the chamber and the observed time is shown in Figure 1.13 for a typical RPC.
Figure 1.12: RPC V-I behaviour and equivalent electrical model

Figure 1.13: Current Stabilisation in RPC
1.4.3 Efficiency Plateauing of RPC

Each RPC before going into the stack undergoes efficiency plateau to find out operating voltage of RPCs [31]. With coincidence of (2 to 3) finger scintillator Paddles trigger has been formed and then strips under paddles are checked for Muon(s). Typical efficiency plateau plot is as shown in Figure 1.14. The main strip and the two adjacent strips on either side are shown in the plots. It is seen that at typical high voltage of 9.9 kV, an efficiency of 99 % is achieved. The current drawn by an RPC chamber of ~ (2 × 2) m² is few hundred nA.

![Figure 1.14: Typical efficiency plot of an RPC](image)

The RPC is a parallel plate gas detector and in the next chapter we present the literature survey beginning with inventions of gas detectors and how RPC were evolved with time. The latest development beyond the discovery of RPC detectors is also highlighted. Why RPCs are chosen for INO-ICAL research program is addressed. Then the literature survey is followed by the Gas System and their evolution with time.
is highlighted. Type of Gas system and methodology of mixing gases is surveyed and finally what type gas mixing system that is best suited for INO-ICAL. Based on this literature survey formation of research problem is made.