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Important developments have taken place recently in neutrino physics and neutrino astronomy. Oscillations of neutrinos and the inferred evidence that neutrinos have mass, are likely to have far-reaching consequences [1]. Impelled by these discoveries and their implications for the future of particle physics, plans have been made world-wide, for new neutrino detectors, neutrino factories and long base-line neutrino experiments. It is in this context that a multi-institutional collaboration has been formed with the objective of creating an India-based Neutrino Observatory (INO).

Considering the physics possibilities and given the past experience, the INO collaboration has decided to build a magnetised Iron CALorimeter (ICAL) detector. In the first phase of its operation, ICAL will be used for atmospheric neutrino physics with the aim of making precision measurements of the parameters related to neutrino oscillations. The detector will be magnetised to a field of about 1.3 T, enabling it to distinguish the positive and negative muons and thus identifying muon-type neutrino and anti-neutrino produced events separately. This capability of ICAL provides an exciting possibility to determine the ordering of the neutrino mass levels. In the second phase, this detector can also be used as the far-detector of a long-base-line neutrino experiment using the neutrino beam from a neutrino factory located at a distance of about 7000 km. Good tracking, energy and time resolutions as well as charge identification of the detecting particles are the essential capabilities of this detector.

The ambitious ICAL detector, of 48 m $\times$ 16 m $\times$ 14.5 m in volume and 50 kt in weight will employ about 30,000 Resistive Plate Chambers (RPCs) of 2 m $\times$ 2 m in area arranged in 150 horizontal layers [2]. This amounts to a total sensitive detector coverage of about 100,000 m^2, which would be one of the largest covered area by a detector anywhere in the world. The primary particle detection mechanism in ICAL is via tracking of muons produced inside the detector mass by the charged current neutrino interactions such as $\nu_\mu + n \rightarrow \mu^- + p$ and $\overline{\nu}_\mu + p \rightarrow \mu^+ + n$.

RPCs are fast, planar, rugged and low-cost gas detectors which find applications for charged particle detection, time of flight, tracking and digital calorimetry. The choice of RPCs for ICAL among other options such as scintillators is driven by their inherent advantages, such as two-dimensional readout from a single detector, excellent spacial and time resolutions, simple and low cost of large scale production and operation. A dedicated R&D programme is currently underway to design, develop and characterise large area RPCs, ultimately leading to their large scale and low-cost production required for the ICAL detector.

An RPC is a particle detector utilising a constant and uniform electric field produced by two parallel electrode plates, made of a material with high bulk resistivity. A gas mixture with a high absorption coefficient and electron affinity is flown through the gap between the electrodes. When the gas is ionised by a charged particle crossing the chamber, free charge carriers that are deposited in the gas gap trigger avalanches of electrons due to the applied electric field. The propagation of the growing number of electrons induces a current on the external, signal pick-up strips [3] [4]. RPCs may be operated in avalanche or streamer modes, which are mainly distinguished by the type of gas mixtures used and the applied voltage [5] [6].

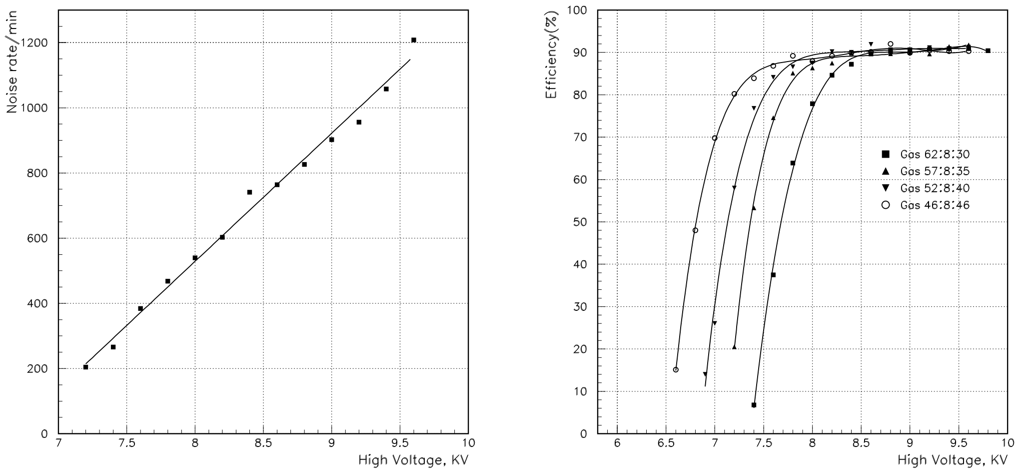

Figure 1: Two most important characteristics of glass RPCs: Noise rate (left panel) and efficiency (right panel) as a function of its applied voltage.

We began our work by developing a large number of single gap glass RPCs of about 30 cm $\times$ 30 cm in area and initially operated them in the streamer mode. The modeled d.c. characteristics of these detectors were studied and confirmed. The noise rate was established to be a reliable way of monitoring the stability of the RPC operation (Left panel of Figure 1). Cosmic ray particle detection efficiency characteristics with several gas mixtures were studied and their efficiency knees and plateaus were established (Right panel of Figure 1). We have also shown that the timing response and timing resolution σ of the RPC improves with the detector voltage and the latter reaches a value of about 1.2 ns at its plateau region, where the recorded efficiencies were over 90% (Figure 2). The charge spectra and its linearity as a function of the applied voltage as well as the inter-strip cross-talk were measured and the latter was found to be about 6%. We have in the process, developed considerable infrastructure such as a gas mixing and distribution system, a cosmic ray muon telescope and a sophisticated data acquisition system.

We have also successfully demonstrated efficient tracking of cosmic ray muons using a stack of 10 RPCs of 30 cm $\times$ 30 cm in area. The RPCs were mounted such that the signal pickup strips of all the chambers were accurately aligned geometrically. The chambers were operated in the streamer mode, using a mixture of Argon, Isobutane and Freon (30 : 8 : 62 by volume). The cosmic ray muon trigger signal was generated by a telescope comprising of a set of scintillator paddles. The detector could be triggered by muons arriving at different angles, by relocating the telescope window. The information

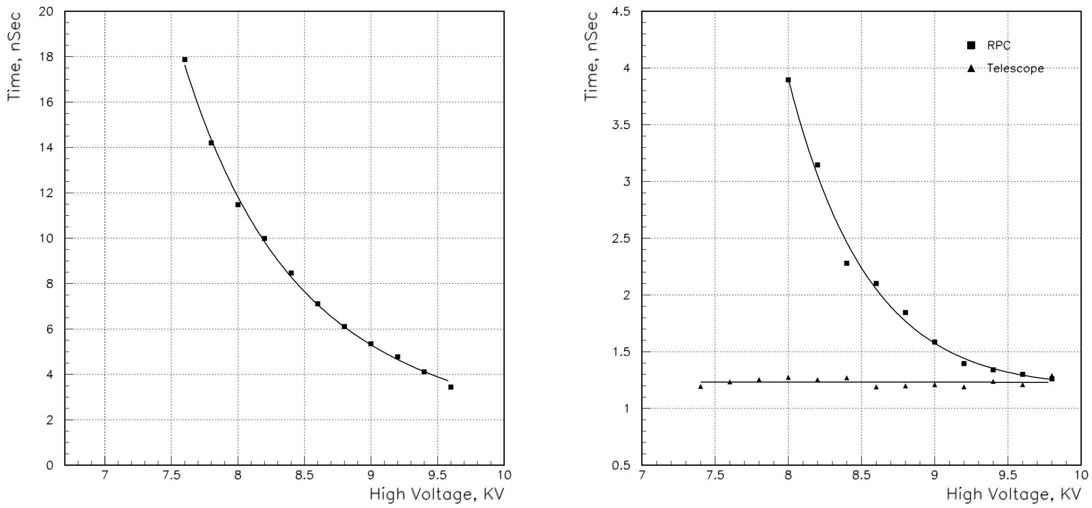

Figure 2: Time response (left panel) and absolute timing resolution (right panel) of a small glass RPC.

recorded in these tests was also used to extract many RPC parameters of interest such as efficiency, noise rate, timing, total hit distributions, strip hit multiplicity distribution patterns and their long- term stability.

Even though the results obtained from the characterisation tests mentioned above were comparable to those obtained by other researchers, we faced a severe problem with regard to their long-term operation. Glass RPCs operating in the streamer mode are known to be stable and have a long lifetime (more than 10 years) as evidenced by the successful operation of these chambers in the Belle experiment [7]. However, our prototype detectors showed signs of sudden aging when operated continuously even for a few months. There was a simultaneous sharp increase in the noise rates and drop in the efficiencies (Left panel of Figure 3).

We have done extensive studies on the inner surfaces of electrodes from the damaged RPCs as well as a large number of local and imported glass samples using Atomic Force Microscope (AFM) and Scanning Electron Microscope (SEM) (Left panel of Figure 3) techniques. Element analysis was also performed using X-Ray Diffraction (XRD) technique both on damaged electrodes and raw glass samples. The structures shown in the AFM and SEM scans were found to be rich in Fluorine, confirming our hypothesis that Freon (R134a) gas contaminated with moisture forms Hydrogen Fluoride (HF), which damaged the RPC. The structures on the damaged electrodes were found to be loose deposits on the electrodes rather than permanent damaged regions on the glass. Even after taking a number of steps towards monitoring and addressing the problem of moisture in the input gases, the detector aging continued. Results from the studies on glass surface quality and elemental analysis, using the above mentioned techniques did not reveal any

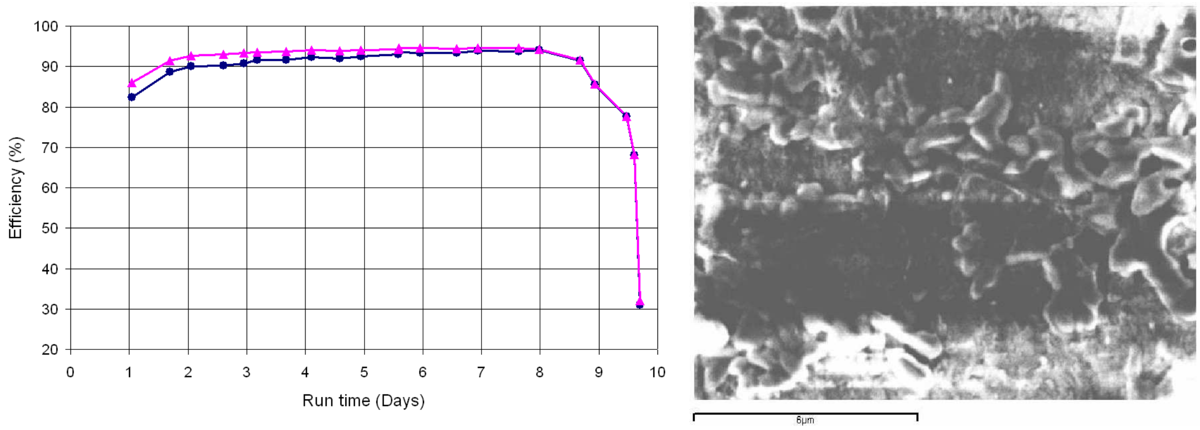

Figure 3: Efficiency time profile plot of an RPC undergoing the aging process is shown in the left panel. The drop in the efficiency is rather sudden. The right panel shows an SEM scan of a damaged RPC glass electrode.

appreciable differences among various glass samples.

We then fabricated a few RPCs of 40 cm $\times$ 30 cm in area, using glass sheets procured from Japan. The same procedures for fabrication and testing as in the case of earlier RPCs were followed for these chambers. Two of these chambers were continuously operated in the avalanche mode for more than two years, in which a gas mixture of Freon (R134a) and Isobutane in the proportion 95.5 : 4.5 by volume was used. The performance of these chambers, characterised by their efficiency, leakage currents and noise rates, remained stable over the entire period of these tests. A comprehensive monitoring system for the periodic recording of the operating parameters of the RPCs together with the ambient parameters such as temperature, pressure and relative humidity - both inside and outside the laboratory, has been designed and implemented. Using these data, several important correlations between the ambient parameters and the RPC operating characteristics could be established.

RPC fabrication involves deploying a large number of materials as well as many assembly procedures, which influence its characteristics and long-term performance. These include materials such as glass used for electrodes, spacers, buttons and gas nozzles which are needed for assembling the chamber and individual gases used for operation of the chambers. Other materials and procedures crucial for RPC fabrication are resistive coat on the electrodes, epoxies used for gluing together different types of materials, pickup panels used for external signal pickup from the chambers and polyester films used for insulating the pickup panels from the resistive coated electrodes. We have studied a number of different types of these materials and optimised their quality, design or construction. We have also designed and developed a large number of assembly and quality control procedures and developed a number of jigs that are extremely useful in production of good quality detectors. Assembling and gluing of chambers and leak testing of the finished chambers are some of these important assembly procedures. A vacuum jig based on a simple but novel technique to maintain uniform pressure on the glass electrodes was designed and developed, resulting in the uniform spacing between them as well as reliable gluing of RPC gas gap. We have worked closely with various R&D institutions as well as many local industrial houses in developing these materials and designing and developing the assembly procedures.

Resistive coating of the outer surfaces of the electrodes plays a very crucial role in the operation of the RPC detector. After our initial R&D work in developing a suitable coat and its application method, we have collaborated with a local paint industry to develop a suitable paint as well as its application methods, which will be more adaptable for large scale production of the RPCs. We have also started designing paint automation techniques and developed prototype robotic machines for the purpose with help of local industry. We have also explored the alternate and cost effective technique of coating the glass surface using screen printing method. This method can also be used to coat the paint on a PET film which can then be stuck on the glass electrode surfaces.

Proper and efficient functioning of the RPC detector demands pre-mixing or on-line mixing of individual gases in appropriate proportion, together with a controlled flow of mixed gases through the detector. The gas flow could be either in open loop mode or in closed loop mode. In the former, gas mixture leaving the detector is collected in a manifold and vented to atmosphere, whereas in the later, it is collected and re-circulated after appropriately purifying it and adding small fractions of fresh gases. We have designed and developed three generations of gas mixing, distribution and recycling systems. The first generation unit features a single output channel and employs rota-meters to mix the input gas in the required proportion. The mixed gas is stored in a reservoir cylinder and subsequently let flow through the output channel.

We had then designed and developed a more sophisticated PC based gas mixing and distribution system, which works on four different input gases and supplies the mixed gas through 16 output channels. It features Mass Flow Controllers to precisely mix the gases to required proportion and 0.3 mm diameter stainless steel capillaries to ensure uniform gas flow through output channels. We have also succeeded in precisely calibrating all the input gas channels over their entire dynamic range by water displacement and other methods. Units of this design were turned out to be workhorses not only for our RPC R&D programme, but for many laboratories in the country.

The gas volume of the ICAL detector is going to be more than 200 m^3. The open-loop systems described above therefore are not suitable to be adapted to this massive underground detector due to considerations such as high recurring costs, potential environmental hazard and safety. Therefore, we have developed an appropriate technique and are currently building a system to recycle the gas mixture. The exhaust gas from the RPC is collected, individual gases separated using fractional condensation method and reused as source. The pilot unit of this design has been successfully tested and is currently being

being used.

Large area RPCs of dimensions 100 cm × 100 cm required for the ICAL prototype detector stack were successfully developed, built and characterised. They were operated stably in the avalanche mode for a long period of time without any signs of aging. We have built a prototype detector stack consisting of 12 RPC layers of 100 cm × 100 cm in area to track and study cosmic ray muons. The RPCs in the detector stack are operated in the avalanche mode, using a gas mixture of R134a : Isobutane : SF_6 in the proportion 95.5 : 4.2 : 0.3. All the electronics, trigger, data acquisition, monitoring and power supply systems required for this detector stack were designed, fabricated, integrated and commissioned. The main objective of the data acquisition system designed for the prototype detector stack is to generate trigger signal whenever a charged particle passed through the detector leaving a track, based on the hit pattern of the RPC pickup strips and to record strip hit patterns as well as timing of individual RPCs with reference to the global detector trigger. We pickup the signals both on the anode side (negative polarity signals) as well as on the cathode side (positive polarity signals) of the RPC, using pickup panels which are mounted orthogonal to each other on either side of the gas gap. In all, there are 64 pickup strips or electronic channels to be readout - 32 on either readout plane. Therefore, we have to handle 768 electronic readout channels from this detector stack.

The signal readout chain at the front-end essentially consists of fast, high gain, Hybrid Micro Circuit (HMC) based preamplifiers and low-level, threshold leading-edge discriminators, followed by the digital front-ends. The digital front-ends built around a couple of Complex Programmable Logic Device (CPLD) chips handle the important tasks of latching the strip hit pattern on master trigger as well as serially transferring data to the back-end system. It is also here that the pre-trigger signals are generated, which are used by the back-end trigger module built using a Field Programmable Gate Array (FPGA) and produces the master trigger. Finally, the digital front-end system also handles the entire signal multiplexing required both during the event data acquisition as well as during strip signal rate monitoring. The RPC timing data on trigger is acquired using commercial TDC modules. The data acquisition is implemented on a CAMAC back-end, employing many custom built modules, such as control and readout modules. The multiplexed signals from the front-end are sent to the back-end through appropriate router modules. Monitoring of strip signal rates is performed as a periodic background job using scaler modules in the back-end.

We have implemented *in-situ* trigger scheme which uses the strip signals of both the readout planes of all the 12 RPCs that make up the detector stack. This scheme is essentially implemented in a distributed manner spanning between the front-end and back-end sections. Eight level-0 trigger primitives are formed in the AFE boards by *OR*-ing four strip signals as a group from one readout plane of an RPC. Using these, level-1 trigger terms are generated in the DFE board. Finally, level-1 terms are fed into the

CAMAC standard, FPGA based Final Trigger Module (FTM) in the back-end via trigger and TDC router (TTR) boards. The level-2 and the final global trigger is generated by this programmable module.

An on-line data acquisition software was developed in C-language and executed on a Linux host. It was designed to acquire the event data on receiving a trigger and concurrently run various monitoring jobs in the background. The cosmic muon events, data of which is being acquired and stored by the on-line DAQ system, are also displayed simultaneously in real time on the web.

The ICAL prototype detector stack is in continuous operation for about two years and is tracking about half a million cosmic ray muons per day. We have developed a ROOT based sophisticated software package, called *BigStack* to analyse the event, monitor and trigger data. Given below are some of our results obtained by this data.

Every new chamber, as part of its preliminary acceptance and characterisation process, undergoes a cosmic ray muon detection efficiency study, as a function of its applied high voltage. This study essentially involves recording and analysing data on the current, strip hits, charge, timing and noise rate of the chamber at various applied high voltages. We fix the operating point for a chamber at a voltage where the efficiency is well above 90%. Efficiency plateau is the region where efficiency is fairly constant over a wide range of the operating voltage of the RPC. We also derive, from these plateau studies, the best timing resolution of the chamber in addition to measuring its other operating and performance characteristics. Shown in Figure 4 are typical efficiency plateau and noise rate characteristics of a 100 cm × 100 cm chamber.

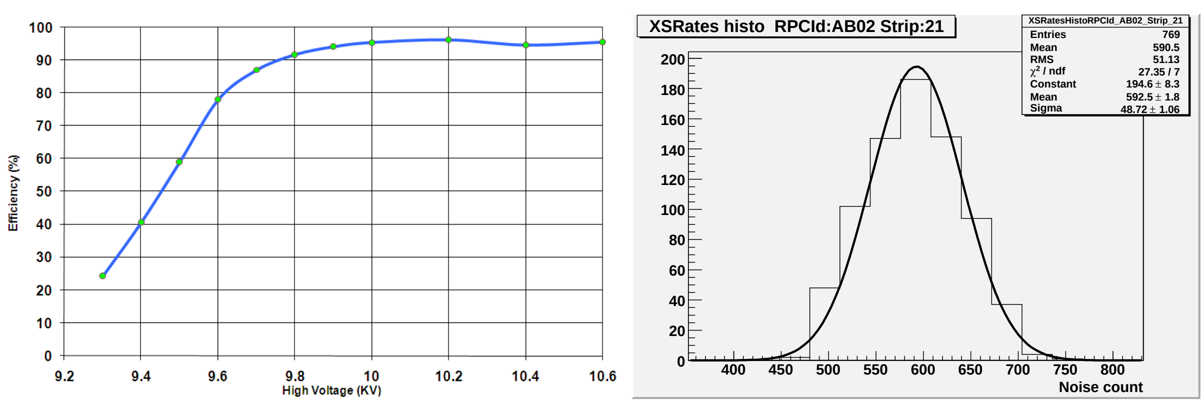

Figure 4: Left panel: Typical efficiency plateau plot of a 100 cm × 100 cm RPC operated in avalanche mode using binary gas mixture of Freon (R134a) and Isobutane. Right panel: Noise rate histogram.

The charge and timing are the two most important parameters in the characterisation studies for an RPC detector. The noise rate, chamber efficiency for detection of charge particles and other derived characteristics depend on the production and efficient processing of the charge induced on the pickup strips for typical charged particles or minimum ionising particles. Similarly, the timing characteristics of the RPC, even while it is deployed in a detector as a *trigger* element, is another important consideration. For example, it is this capability of the RPC, which will be exploited in the ICAL detector for determining the directionality of the particles - whether the particle is traversing the detector from top to bottom or vice versa. This is an important measurement in the context of atmospheric neutrino studies. Shown in Figure 5 are the charge and timing distributions of an RPC under test, recorded on cosmic ray muon trigger. It is interesting to note the Landau distribution in case of charge plot. The sigma of the fitted distribution is about 11% of the most probable value. We obtain a typical time resolution of about 1.7 ns from a Gaussian fit of the timing distribution.

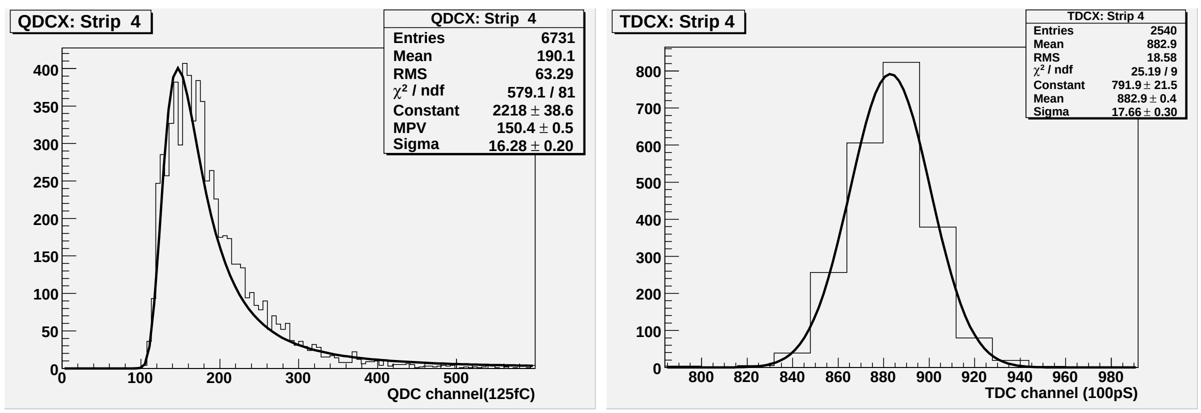

Figure 5: Typical charge and timing characteristics of an RPC. It may be noted that the charge distribution is of a single strip, while the timing data is obtained from an entire readout plane by logically summing up all the strip signals.

The timing data of an RPC is the time interval between the cosmic ray muon trigger and the time of the associated hit in that RPC. The average time resolution obtained by the RPC stack is in the range of 2 ns. We also measure the relative timing between the reference RPC and individual RPCs in the stack. As expected these relative time resolution plots are narrower and provide time resolutions of less than 1.5 ns. This data, which is summarised in Table 1 shows that the intrinsic time resolutions of the RPCs are better than that of scintillator paddle detectors used to build the cosmic ray muon telescope.

The cosmic ray muon data, apart from being used to monitor the day-to-day status as well as long-term stability of the detector stack and its associated electronics, is also used for detailed analysis of the stack's performance and precision measurements. The cosmic ray muon tracks, which are recorded in the stack are being used to study several performance parameters of the RPCs.

Tracking efficiency of RPCs in the detector stack for both the readout planes are computed. This efficiency is different from the efficiency that we usually obtain from the plateau characteristics of a newly fabricated RPC and is a more realistic parameter from

Table 1: Summary of time resolution measurements of the RPCs in the stack. All the time units are in ns. Columns of particular interest are absolute and relative sigmas.

RPC Id	HV(kV)	Abs. Mean	Abs. Sigma	Rel. Mean	Rel. Sigma
AB06	09.8	49.53	2.06	-7.64	1.41
JB00	09.6	46.00	2.32	-4.47	1.67
IB01	09.8	42.31	2.15	-0.64	1.63
JB01	09.6	42.55	2.28	-0.87	1.58
JB03	09.8	43.75	2.26	-2.18	1.44
IB02	09.8	38.49	2.31	3.27	1.38
AB02	09.8	42.77	2.53	-1.21	1.51
AB01	09.8	35.30	2.16	6.33	1.71
AB03	09.8	45.82	3.23	-4.55	1.99
AB04	09.8	41.66	2.42	-	-
AB07	09.8	40.61	2.47	0.96	1.35
AB08	09.8	41.56	2.80	0.31	1.82

the point of view of its performance in a detector. A small area on the RPC mapped usually by a scintillator paddle based cosmic ray muon telescope window, is tested in case of studying the plateau characteristics. The tracking efficiency as obtained in a detector on the other hand represents the entire surface area of the RPC, as it is calculated based on the cosmic ray muon tracks traversing through its entire area. Table 2 shows the tracking efficiencies of various RPCs in the stack.

The track impact position on the chamber under test can be determined essentially by the same procedure as above. Strips which lie on the fitted track and recorded by the DAQ system as hits are determined for every event. The frequency distribution of these strips for the X-readout plane is shown in the left panel of Figure 6. The distribution represents the trigger acceptance criterion in force for the detector stack, which in turn determines the fiducial volume of the detector for trigger generation and hence for the data analysis.

The chamber cluster size or strip multiplicity, which may be defined as the average number of strips fired for a minimum ionising particle hit, is practically computed as the average value of the cluster size distribution. Apart from its dependence on gas mixture and surface resistivity of the electrode coating among other factors, the cluster size is a function of the applied high voltage and can be used as one of the criteria to accept a chamber during large scale production. Typical cluster size or strip multiplicity plot of an RPC is shown in the right panel of Figure 6. The average strip multiplicity of the RPCs for cosmic ray muon data is found to be about 1.4.

We have also studied the distribution of the residuals between the fitted track and hit pickup strip coordinates. Residual of a hit strip in a layer is defined as the difference

Table 2: Tracking efficiencies of the RPCs in the stack as determined by the tracking of cosmic ray muon events. The layer-wise efficiencies are calculated as the ratio of the number of strip hits on the cosmic ray muon track to the number of tracks passed through the detector stack (and through that layer).

RPC Id	Tracks	Hits	Efficiency(%)
AB06	130118	122649	94.3
AB07	130420	124796	95.7
AB10	130457	126355	96.9
AB11	130472	126390	96.9
AB09	130472	125840	96.4
IB02	130465	126660	97.1
AB02	130464	127473	97.7
AB01	130456	127668	97.9
AB03	130439	126573	97.0
AB04	130404	127115	97.5
AB12	130286	122066	93.7
AB08	129272	123490	95.5

between the centre of the strip and the fitted track hit position on that particular layer. Typical residual distribution plot of a layer in a cosmic ray muon tracking run is shown in left panel of Figure 7. The shape and width of the distribution is as expected for actual width of our pickup strips being 28 mm and separated by 2 mm gaps. The distribution also peaks at the origin or centre of the strip, which is the minimum logical unit of the hit position on the RPC.

Uniformity of response is one of the most important requirements for large RPC systems, such as those planned to be deployed in ICAL detector [8]. The cosmic ray muon tracks recorded in the stack are used to build a surface profile or tomography of the RPCs

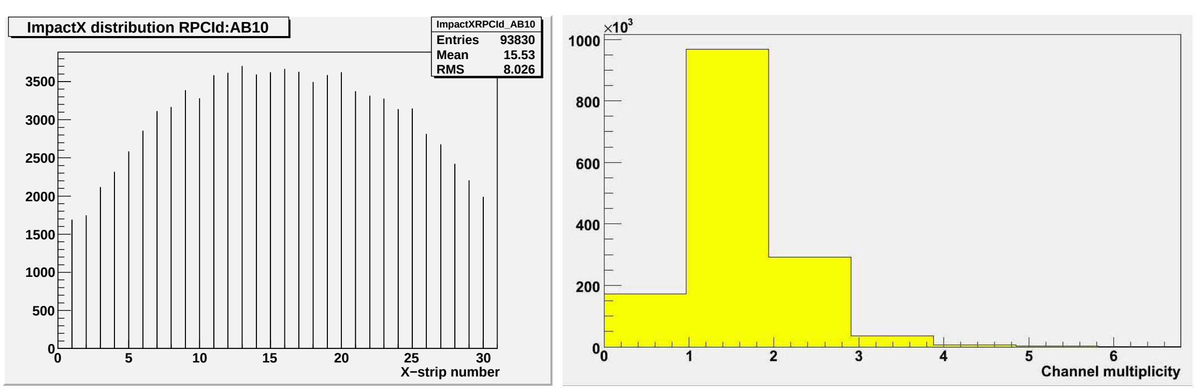

Figure 6: Left panel: Track impact position distribution of an RPC in the stack using cosmic ray muon data. Right panel: Typical cluster size or strip multiplicity distribution plot of an RPC.

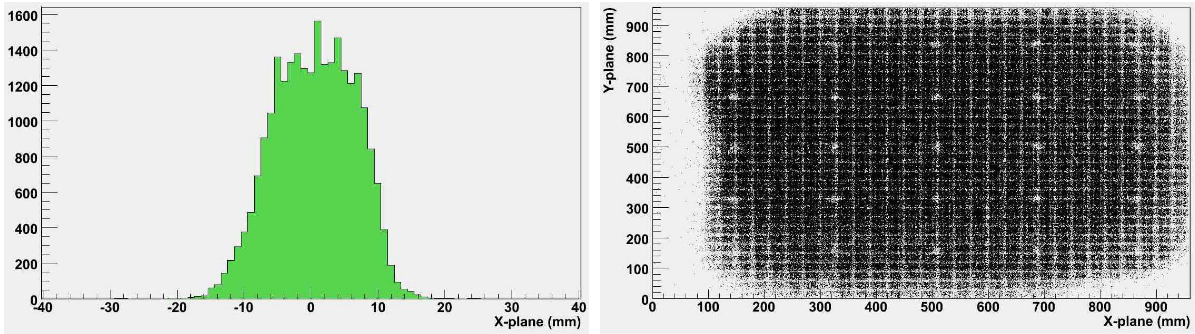

Figure 7: Left panel: Residual distribution of cosmic ray muon track position through an RPC. Most of hits are distributed within 20 mm, and the RMS is about 6 mm. Right panel: Surface map or tomograph of an RPC using cosmic ray muons.

under test. A typical surface map of an RPC is shown in the right panel of Figure 7. The map represents uniform response of the RPC for charged particle detection over its entire active area. The width (28 mm) of the pickup strips used for the RPC readout, the inter-strip gap (2 mm) as well as the dead space due to button-shaped spacers (11 mm in diameter) are clearly visible in the surface map.

The RPC detectors are expected to work stably for 10-15 years in the ICAL experiment. Therefore, studying the stability of their operation over long periods of time is essential. We have used the operating parameters of the RPCs, such as dark current, individual strip counting rates (or noise rates) as well as the detection efficiencies as excellent tools for monitoring the long-term stability of the RPC detectors. Parameters such as dark current and noise rates in particular, show variations during a 24-hour time period. These variations correlate faithfully with changes in the ambient parameters like are temperature, relative humidity and barometric pressure. Since the RPC is a gas based detector, variations in the ambient parameters are expected to have some effect on its operation [9]. We could also use the measured data of temperature and barometric pressure in order to correct the RPC efficiency for the changes in the ambient parameters [10].

We have successfully built and characterised the glass RPCs of 2 m $\times$ 2 m in area that will be used for the INO's ICAL experiment. These detectors are operating flawlessly till now, essentially concluding the detector R&D phase of the ICAL detector construction. However, we would now focus on simulating their detector physics, characteristics and problems. Though a lot of work in this direction is already done by other researchers in the field [6] [11] [12], it is imperative that we develop our own understanding and experience in this field, since we plan to deploy these devices in huge number in the ICAL detector. Some of the aspects which will be of particular interest for us are optimisation of gas mixture and flow rate on the characteristics and long-term performance of the RPCs. The characterisation of RPC signal induction and transmission to the front-end electronics and their performance in terms of its various components such as electrodes, electrode coating and pickup panels needs to be explored further. These studies will not only improve our knowledge on the detector physics of these devices but also will result in smooth and cost effective running of ICAL detector.

A magnetised ICAl prototype detector, of about 1 m^3 in active volume with 12 layers of RPCs, each of about 100 cm $\times$ 100 cm in area, was assembled. It will be interesting to study the performance of the RPCs in this detector under the influence of magnetic field. Degradation of RPC characteristics such as the spacial and time resolutions, if any may be studied.

In the ICAL detector, the up-going muons, which are produced by the ν_μ interaction inside the detector volume, must be discriminated from the down-going cosmic ray stopping muons. This can be achieved by using the length of the track left in the detector by the traversing particles as well as time resolution of the RPC detectors. We are currently working on determining the $\beta(= v/c)$ value of the cosmic ray muons tracked by the stack.

Optimised front-end electronics plays a crucial role in the efficient deployment as well as to preserve the characteristics of these detectors in the large scale experiments. RPC characteristics such as its time resolution, cross-talk and stability of long-term operation could be improved substantially, if it is equipped with a superior front-end electronics. As part of the detector R&D programme, we have taken up design and fabrication of a multi-channel ASIC front-end chip, comprising of differential design, high-gain, high-speed preamplifier and comparator stages. A comprehensive programme is in full swing to design and develop front-end electronics, data acquisition, trigger, slow control and monitor systems needed for ICAL detector.

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