Design and Simulation Studies of Resistive Plate Chambers

(Ph.D Progress Report)

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Abstract

We had begun our development work on Resistive Plate Chambers (RPCs) a few years ago by building and characterising a large number of small prototype RPCs, which were fabricated using glass procured from local industry and operated them in the high gain streamer mode. While, these chambers showed good performance initially, they had suffered from aging problems when operated continuously for long durations. After ruling out some possible causes - such as gas quality for example, for the aging problem, we had built a few RPCs using float glass, which was imported from Japan and operated them in the low gas gain avalanche mode. These RPCs have operated in excellent condition for the past two and a half years without showing any signs of aging until we had stopped the run end of last year. These results have for the first time indicated a possible role of electrode glass in the aging problem.

During the past year, we have continued our active research and development work on various design and performance aspects of large area RPCs. This has been mainly a year of further developments as well as precision measurements on materials, processes, fabrication, operation, characterisation, long-term stability and performance aspects of large area RPCs. Our understanding and skills about these new detectors has now reached a matured stage, which enables us to fabricate and operate RPCs of $1m^2$ in area routinely with almost zero failure rate. We have tested these chambers thoroughly, measured various performance parameters and found that the chambers show excellent characteristics and stability. We have refurbished and improved the capabilities of the gas mixing and distribution system, cosmic ray muon telescopes, electronics and data acquisition systems of the RPC test stands. We have developed and made extensive studies on various materials and processes involved in fabrication of the RPCs. We have identified appropriate agencies and local industries and formed various collaborations and working methodologies for production of the materials as well as fabrication of RPCs.

We have fabricated 12 large area RPCs of Iron CALorimeter (ICAL) prototype detector design, arranged them as a detector stack and are currently operating them uninterrupted for about a year now. We have also completed design, fabrication, integration and commissioning of the entire electronics, trigger, data acquisition and on-line monitoring systems meant for the operation of ICAL prototype detector. We have designed and built a new sophisticated 16-channel gas mixing and distribution system which will be used with this detector. We have also designed and built a 35 ton 1.5 Tesla magnet required for this detector and completely commissioned it at VECC, Kolkata.

Finally, we have made a number of presentations based on our work mentioned above at various national and internatonal conferences and symposia as well as in India-based Neutrino Observatory (INO) collaboration meetings held during the past year. Some of our recent work is currently in the process of appearing as publications.

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1 Introduction

Neutrinos are one of the fundamental particles, which make up the universe. They are also one of the least understood. Neutrinos are electrically neutral and were initially thought to be mass less. There are three types or flavours of neutrinos known. Recent evidences seem to indicate that neutrinos not only have mass, but also experience mixing among these flavors. This leads to the phenomena of neutrino oscillations that can explain the discrepancy between theory and observations about its flux. Neutrino mass can also be indirectly estimated by detecting its eventual oscillations. The existence of non-zero mass for neutrino has profound implications on fields as varied as nuclear physics, particle physics, astrophysics and cosmology.

Historically, the Indian initiative in neutrino physics experiments goes back to several decades. In fact, the first atmospheric neutrino event was recorded at the Kolar Gold Fields (KGF) underground laboratory nearly forty years ago. The KGF experiments had spanned several decades involving a systematic study of neutrinos and its related exotic processes at great depths underground. To exploit this valuable expertise for the emerging new area of observational neutrino physics, an idea to construct a neutrino detector by an India-based Neutrino Observatory (INO) collaboration was mooted several years ago. This proposal has subsequently been formalised with a Memorandum of Understanding signed by several Indian research institutes and universities.

The proposed neutrino detector will have a modular structure of lateral size 48m $\times$ 16m and height 12m with iron plates used as absorber and RPCs as active detector elements. It will comprise of 140 layers of horizontally arranged iron plates of about 6cm thickness, interleaved with 2.5cm gap between successive layers of iron plates to house the RPCs. The iron plates will be magnetised at a field of $1.2 - 1.3$Tesla. The total mass of this detector will be about 50kTon.

It is proposed that we use large area RPCs of surface area 2m $\times$ 2m for this detector. The total number of detector elements that we therefore need to build is about 27,000. Float glass of about 216,000m^2 in area will be needed to meet this requirement. Assuming a two-dimensional signal pickup pitch of 3cm on either surface of the glass RPC, we need to instrument about 3,600,000 signal channels. While, we need to record Boolean status information (i.e. one bit per channel) for all these channels, the signal channels can however be combined for recording signal arrival time information.

The main characteristic of such a detector would be a clean identification of muon tracks, which are associated with the neutrino interactions that take place inside the detector with good spatial and time resolutions. In addition, the presence of the magnetic field will distinguish positively and negatively charged particles. These properties meet very well the conditions required to unambiguously identify muon neutrino oscillations.

2 Review of our earlier work

Principles of operation of RPCs and overview of the field, along with our initial work on development and characterisation of RPCs have been reported in my Ph.D Credit Seminar Report[1, 2]. A detailed account of prototype chambers that we had designed and fabricated, gas mixing and distribution system, cosmic ray muon telescope and data acquisition systems that we have designed and developed was given in my earlier Ph.D Progress Report[3, 4, 5, 6]. Extensive work and results that we had achieved on glass electrode characterisation, electrode coatings, development of a new multi-channel gas system, long-term stability of RPCs and tracking of cosmic ray muons using RPC stack was reported subsequently[7, 8, 9]. We have reported preliminary results of our detector development work in an interim report on the INO feasibility study, which was submitted to the funding agencies[10]. This was followed by a detailed and upgraded report[11] that we had produced last year. We have also completed a detailed project report on construction of the underground cavern to house the ICAL and future detectors as well as various infrastructural as well as operational facilities required in the cavern[12]. A brief review of this earlier work is given below.

We have fabricated several dozen *small area* glass RPCs of dimension 30×30 cm^2 as well as many *large area* chambers of dimension 120×90 cm^2. We have developed a number of jigs and tools that help in ascertaining the quality of raw materials that we use to build the RPCs as well as during various fabrication stages of the RPCs.

A gas mixing unit capable of mixing four individual gas components and control the mixed gas flow through the detector chambers has been designed and developed. We have implemented various changes in the gas system in order to address the problem of reducing the moister levels in the gas mixture. These include installation of silica gel and molecular sieve based moister filters as well as fine dust filters in the gas input line. We have also assembled and installed an alumina based in-line filter with in-situ charging facility. Subsequently, we have designed a six-channel rotameter based gas distribution system, which has helped us maintain absolutely constant flow rate through the chambers. Finally, we have also implemented substantial improvements in the gas system, such as using low vapour pressure oil (DC704) in the output gas bubbles, replacing the gas lines with hydrophobic pipes and fittings, as well as installing an in-line Mass Flow Controller (MFC) for a better gas regulation through the main input gas line.

All the prototype chambers have been tested for their performance using a scintillator paddle based cosmic ray muon telescope, consisting of four cosmic ray muon trigger and two veto paddles. A suitable telescope support structure has been designed and built employing light-weight aluminum extruded channels. The cosmic ray muon telescope was found to exhibit excellent stability.

A data acquisition system for RPC testing has been designed and developed using NIM and CAMAC electronics which is available in the laboratory. The telescope monitor and RPC data acquisition CAMAC crates are individually controlled by dedicated PC hosts, in which the on-line data acquisition system software run. While the telescope monitor system collects, displays and stores all scaler counter data at equal chosen time intervals continuously, the RPC system waits for the Cosmic ray muon trigger, to initiate data acquisition for that event. On trigger, the timing(TDC), charge(ADC) and rates(scalers) data are acquired, displayed and stored. The data collected by the on-line systems is analysed using standard physics analysis software packages such as PAW and ROOT. Apart from this, various slow monitor parameters such as ambient temperature, relative humidity, gas flow into the RPC, applied high voltage, chamber current etc. are also recorded so that we can easily correlate various results or problems with these parameters.

We have started our studies by looking at some of the basic operating characteristics of the chambers, such as RPC pulse profiles, voltage−current relationship, individual counting (or noise) rates of the RPC and so on. We have established a reliable way of monitoring the stability of the chamber based on its noise rates. We have obtained chamber plateau efficiencies of over 90% for various gas mixtures. We have confirmed that the RPC is operating with a good energy resolution by studying the pulse height (charge) distributions of small RPCs operating them at various high voltages. We have made detailed measurements on the charge-time linearity, time response as well as the time resolution of the RPCs and obtained a typical timing resolution of about 1.2nSec while the RPC is operating on its plateau. The chambers that we had fabricated have shown cross talk of about 6% between the adjacent pickup strips.

In connection with the aging problem of the RPCs, we have also studied various RPC operating parameters just before it is getting damaged. These include monitoring the individual pixels' (overlapping areas between two strips) rates on surface of the RPC to locate sudden increase in noise rates from a region, if any before the chamber is damaged. We have also devised a parameter called streamer size and monitored the same during the RPC tests to see if the size increases steadily with long term operation. We have also looked at noise rate history of individual strips of this chamber and found that certain strips tend to shot up with their rates with continuous operation.

While working mainly on glass RPCs of various designs and sizes, we have also made attempts to gain experience with bakelite based RPCs. We had operated a couple of bakelite RPCs of CMS end cap design along with some of the glass RPCs, which were fabricated by us. While we had used a three component gas mixture of Argon, Isobutane and Freon (R134A) in a typical proportion of 30:8:62, for avalanche mode of operation, we have used a binary mixture of Freon and Isobutane in a typical proportion of 95.5:4.5 for these tests. We have also used low noise, fast preamplifiers on the RPC strip signals in order to compensate for the low amplitude signals from chambers operated in avalanche mode. While the glass RPCs sustained only for about two months of continuous operation on their plateau voltages, the bakelite RPC didn't show any signs of aging or damage. This has demonstrated that if the moister in the gas indeed is the key issue for the possible problem, it seem to affect only glass electrodes, irrespective of the RPC's mode of operation, i.e. avalanche or streamer. This was our first such demonstration.

In line with all necessary changes and improvements being carried out in other subsystems of RPC test stand, we have made many changes in the readout and data acquisition system as well. One of the major changes in this direction is to expand the DAQ system to read all individual X and Y strip data in parallel. This has helped us to conclude that when there is sudden increase in the noise rate of the RPC, the increase is not uniformly spread across the area of the RPC, but rather from certain localised regions. Dark current of an operating RPC is an important parameter to monitor its stability. We have therefore decided to power the RPCs with high voltage power supplies which offer current monitor ports of good current resolution. We have developed a NIM module to condition these signals suitably, so that they can be fed into commercial peak sensing ADC modules.

During operation of *small area* RPCs, we have noticed that the operating parameters of the RPCs - dark current and noise rates in particular have shown variations on a definite 24-hour cycle. The ambient parameters that are most conspicuous of the 24-hour cycle are temperature and barometric pressure. Since the RPC is a gas based detector, variations in these parameters are expected to have considerable effect in its operation. We can also use the measured parameters of temperature and barometric pressure along with the RPC operating voltage in order to correct the RPC efficiency for the changes in the ambient parameters. We have therefore procured ambient parameter sensors for barometric pressure, temperature and relative humidity and interfaced them to the data acquisition system for recording these data routinely along with RPC test data.

While the problem of short lifetime of the glass RPCs produced by us was being investigated, we had fabricated a few RPCs using glass procured from Japan. Two of these chambers were continuosly operated in the avalanche mode, in which a gas mixture of Freon (R134a) and Isobutane in the proportion 95.5:4.5 by volume is used. A comprehensive monitoring system for the periodic recording of the currents of these two RPCs as well as the ambient parameters such as temperature, pressure and relative humidity both inside and outside the laboratory has been designed and implemented. This longterm has been terminated this year after successfully operating these chambers without any signs of aging over a period of two and a half years.

We have setup a separate laboratory and installed a new Mass Flow Controller (MFC) based 16 channel gas mixing and distribution system. The system works on four input gases - Argon, Freon, Isobutane and SF_6. Ten RPCs were fabricated using the same materials and fabrication procedures and parameters as those described earlier. Float glass of thickness 2 mm and size 30 cm $\times$ 30 cm was used. The RPCs were mounted as a stack such that the signal pickup strips of all the chambers were well aligned geometrically. The chambers were operated in the streamer mode, using a mixture of argon, isobutane and freon (30:8:62 by volume). The operating high voltage for the tests was kept at 8.6 kV. Using the above stack, we could record some interesting cosmic ray muon induced tracks. Muons arriving at different angles could be captured simply by relocating the telescope window. This has demonstrated that indeed these prototype chambers are capable of effectively tracking cosmic ray muons. The information recorded in these tests was also be used extract other parameters of interest, such as efficiency, noise rate and timing of individual RPCs and their long term stability[13].

We have initiated extensive glass characterisation studies to study and compare glass samples of various makes using diverse techniques such as AFM, SEM, XRD, EDS, transmittance and reflectance[22]. We have also used the same techniques to study the effected glass electrodes in case of damaged or aged chambers. We have improved, studied and optimised electrode coating techniques. We have also begun our attempts to development many materials and processes which are required for the fabrication of chambers, using local industrial support. We have also made a detailed studies on the effect of temperature and relative humidity on the stability and performace of the RPC.

Production of high performance and reliable RPC chambers involves choosing the right type and quality of materials as well as optimisation of various assembly and quality control procedures involved in the fabrication. We have studied a number of different type and quality of these materials and optimised most of these items. We have also designed a developed a large number of assembly and quality control procedures and invented a number of useful jigs that are extremely useful in production of good quality detectors. We have worked closely with various R&D institutions as well as many industrial houses in developing these materials and designing and developing the assembly procedures.

We have done extensive pulse profile characterisation studies of RPCs as well as effect of mixtures on the same. It is proposed that we build a prototype of the magnetised iron calorimeter and study cosmic ray muons using the same, in order to understand and estimate performance of the final ICAL detector. Based on our detector R&D and development of various materials and fabrication procedures, we have started building RPCs of $100 \times 100\text{cm}^2$ in area. We have also designed and built electronics, trigger, data acquisition and on-line monitoring systems for this detector.

3 Longterm stability tests of RPCs

Although glass RPCs operating in the streamer mode are known to be stable and have a long lifetime, those made by us earlier had a much shorter life time. As mentioned above, while the problem of short lifetime of the glass RPCs produced by us was being investigated, we had fabricated a few RPCs using glass procured from Japan. Two of these chambers (named J2 and J3) are currently being operated in the avalanche mode, in which a gas mixture of Freon (R134a) and Isobutane in the proportion 95.5:4.5 by volume is being used. The longterm stability tests were started on these two chambers from September 2005. As can be seen from the plots in Fig. 1, the performance of these chambers, characterised by their efficiency, leakage currents and noise rates, have not changed over the last two and a half years. Shown in the plots is the combined efficiency of these chambers over a period two years along with the ambient temperature, barometric pressure and relative humidity. We have stopped these longterm stability runs end of last year. These tests have indicated that the aging problem associated with the previous RPCs is related to the quality of glass used to fabricate those RPCs and their operating mode. We have again this year fabricated a a large area RPC using local glass and tried to operate the chamber in streamer mode using the streamer gas mixture. But the chamber's effciciency dropped suddenly after surviving barely for a few weeks. This has reconfirmed our earlier conclusion on the issue of detector aging[24].

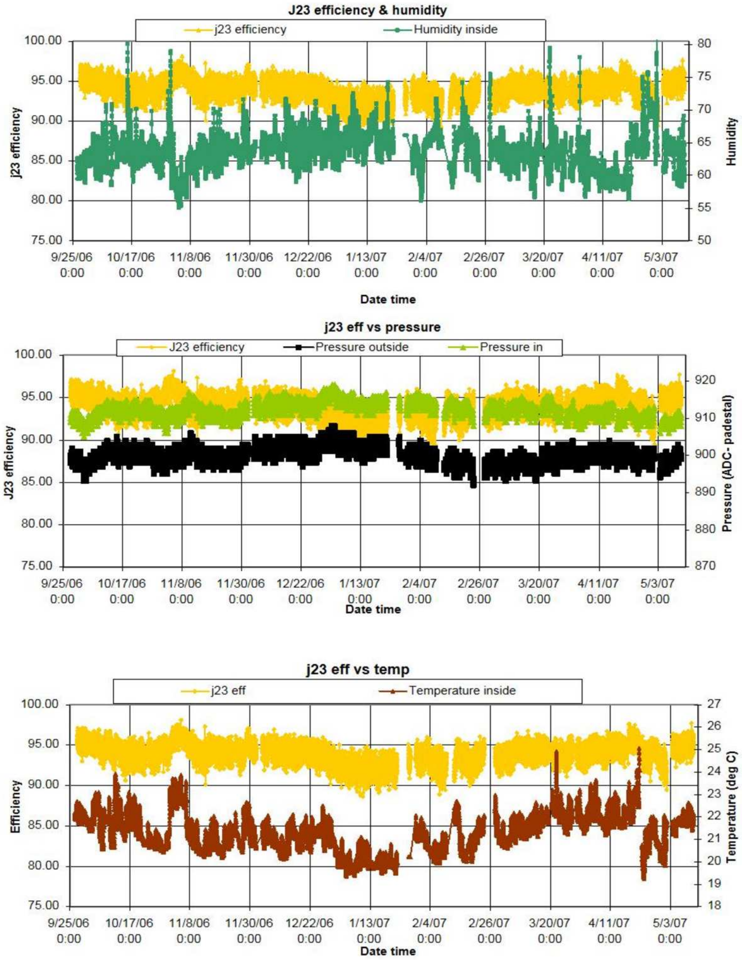


Figure 1: Long term stability monitoring plots of J2 and J3 RPCs

4 Development of honeycomb pickup panels

Pickup panels are mounted on either side of the RPC detector volume. The charge produced inside the gas volume due to passage of a charged particle through the chamber, induces signals on the strips of the pickup panels due to capacitive coupling. Good design of pickup panel is very crucial not only in terms of its mechanical dimensions, but also in terms of its electrical properties. Pickup panels are typically designed using a dielectric medium between two metallic layers. The metallic layer facing the RPC detector volume is segmented as per the required spatial resolution from the chamber. As far as the mechanical properties are concerned, it is ideal to have the pickup panels to be thin, so that the overall thickness of the finished chamber could be minimized. On the other hand as far as the electrical properties are concerned, it will be ideal to have the characteristic impedance of the strips so formed to match to that of the front-end electronics so that signal reflections can be minimised. Another important consideration is attenuation of the pickup strips, which should be minimised as well. So far,

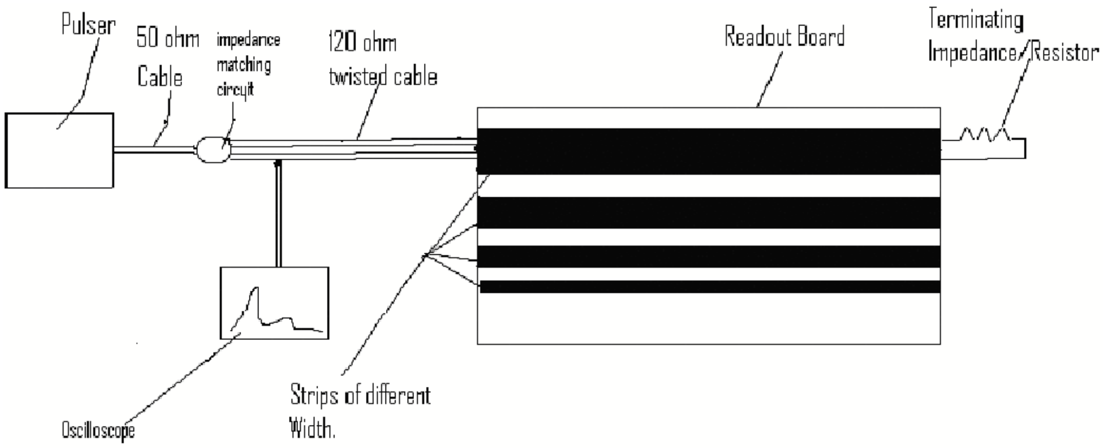


Figure 2: Experimental setup for measurement of characteristic impedance of pickup strip

we have used pickup panels made of foam on either side of which aluminium foils are pasted or G-10 panels which are typically used to fabricate electronic printed circuit boards.

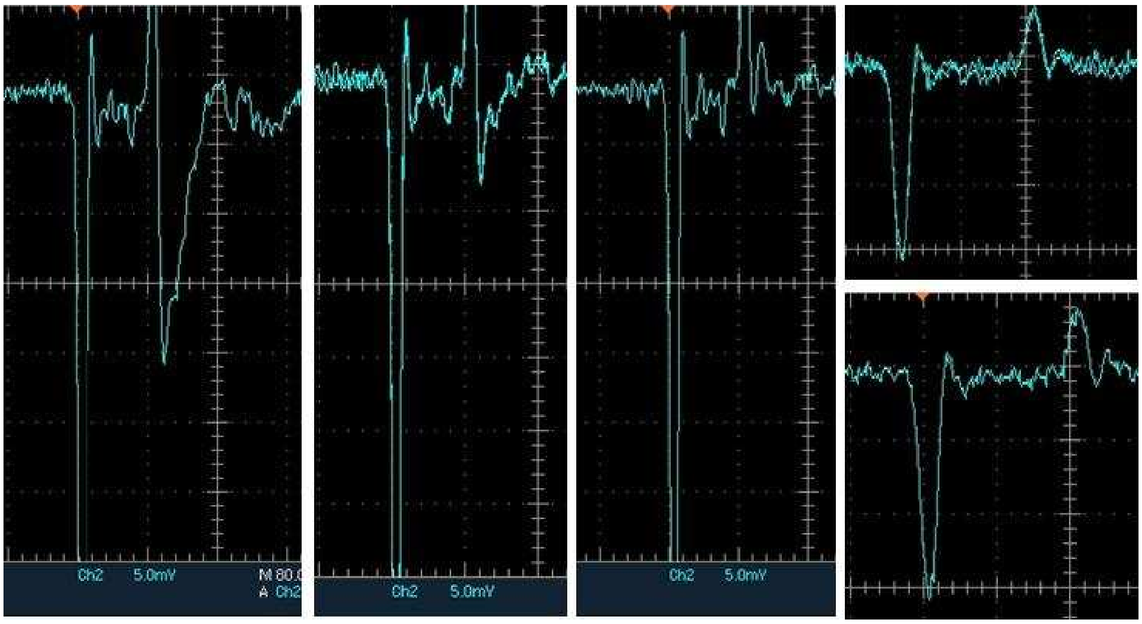


Figure 3: Typical signals seen on oscilloscope during measurement of characteristic impedance

We have also reported our extensive characterisation studies of these materials especially their characteristic impedances and dielectric constants in our earlier progress reports. We have shown that the characteristic impedance of pickup strips of 30mm width, which are realised by machining the aluminium foil on one side of the composite, is typically about 110Ω. Since typical input impedance of the front-end electronics is 50Ω, this requires use of impedance matching circuits between the pickup strips and front-end electronics.

In addition, there is also a requirement for designing a suitable arrangement for providing mechanical support and rigidity to the RPC detector. In case of using foam based pickup panels, this requirement is met by designing a box-like structure using aluminum around the RPC, which has resulted in increase thickness of the RPC in addition to the increased cost of its fabrication. Design of the ICAL detector structure is carried out by assuming minimum thickness for the active detector elements in order to accommodate 140 of these layers as well as to minimise the magnetic field variations inside the structure. Due to all the reasons mentioned above, it was decided to work on development of a solution that combines the two functions, namely that of pickup panels and support structure for RPCs.

Plastic honeycomb panels of 5mm thick laminated on one side by 100μm thick aluminum sheet and the other side by 50μm thick copper sheet were developed by us with help of an industry. Pickup strips of 30mm width are realised by employing the same machining technique on the copper sheet. Aluminum side acts as the signal reference layer. The honeycomb panels were found to be an excellent solution to the mechanical support to the RPC, since it offered better rigidity to the detector with much lesser weight than that of aluminum.

We have used the experimental setup shown in Fig. 2 to measure the characteristic impedance of the pickup strips on the honeycomb panel. A waveform generator is used to send a pulse through a 50Ω cable. This cable is matched to a pair of twisted pair lines of characteristic impedance of 110Ω using a impedance matching network. While one line goes to an oscilloscope for measurement, the other is connected to the pickup strip whose characteristic impedance we want to obtain. A variable resistor is connected between the two plates of the pickup and adjusted such that the reflection from the far end disappears. This is the characteristic impedance of the strip. A typical sequence of signals seen on the oscilloscope for a case of un-terminated strip to the matched termination resistor values are shown in Fig. 3 in the close-wise direction starting from the leftmost trace. This value can be calculated using the dimensions of the pickup strip and the dielectric constant of the foam material. Our measured values were found to agree well with the calculated values.

5 Development and study of electrode coatings

Resistive coating of the outer surfaces of the electrodes plays very crucial role in the operation of the RPC detector. While surface resistivity of this coating should be small enough so that the bias voltage that is required for the RPC operation can be applied on these coats, it should be high enough to render it *transparent* to electric pulses generated by the charge displacement in the gas gap. This way, the charges produced inside the gas gap on passage of a particle, can induce electric signals on the external metallic pickup strips, which are capacitively coupled to the gap. Needless to say that the uniform response of the RPC is dependent on the uniform resistivity of the coating across the surface of the electrodes. It is also important for longterm stability of the RPCs, that the binding strength of the coat to the electrodes is strong. Finally, the materials used as well as the technique employed for coating should be adaptable for large scale industrial production.

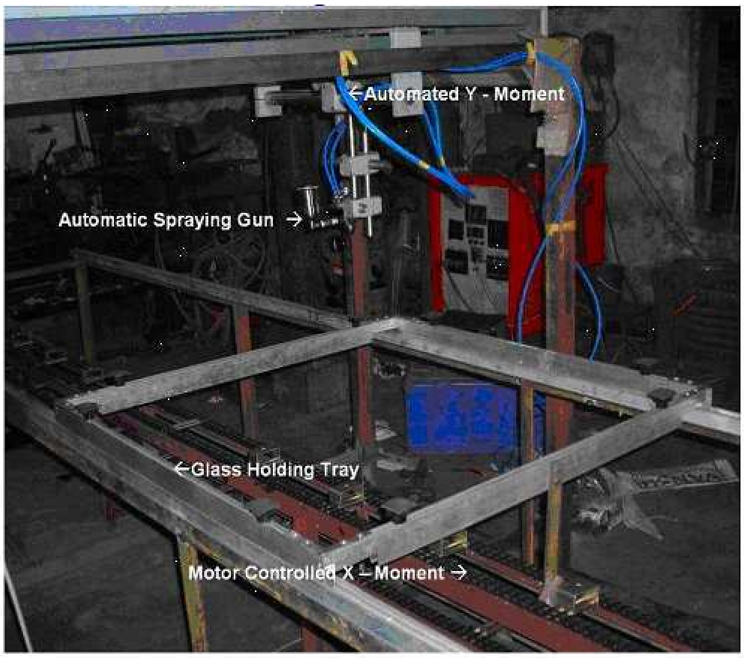


Figure 4: Automatic glass painting machine under development

There is another important consideration of this electrode coat on the performance of the RPC. Every charged particle passing through the RPC, produces a tiny charge spot of about 0.1cm^2 in area. This area is too small to result in any noticeable cross-talk between two adjacent pickup strips on which signals are induced. However, if the surface resistivity of the graphite coat is *too* small, the induced charge spreads laterally across the graphite coat, producing large cross-talks between the pickup strips and thus severely affecting the position resolution of the detector.

We have described earlier[7] our work on development of a suitable semi-resistive paint using colloidal grade graphite powder as well as the tools and jigs needed for its application on the glass electrodes and for measurement of the surface resistivity of the coat obtained. Subsequently, we have collaborated with M/s Kansai-Nerolac Paints Limited on improvising this paint as well as the application methods, which will be more adaptable for large scale production of the RPCs. This paint uses modified acrylic resin as binder, conductive black pigment and solvents which include aromatic hydrocarbons and alcohols. At room temperature the coated surface dries in about 10 minutes while complete drying takes about 18 hours. The spraying is done with gun equipped with a nozzle size of 1.3-1.6mm at a pressure of 4 kg/cm^2 with the glass plate kept at a distance of 20-25 cms. We have also optimised various components of this paint and obtained excellent final results.

Another important aspect, where we have focused our efforts in this area is about the paint

DC-20 (% by weight)	DC-1000M (% by weight)	Resistance/Square	Remarks
0	100	> 50 M?	+10% Sericol Vionyl
10	90	> 50 M?	
20	80	5 to 10 M?	After drying
50	50	4.8 K?	
100	0	160 ?	
40	60	5-7 K ?	Single coat
		3.1 to 4.3 K ?	Double coat
30	70	40 K? on paper	No reducer
30	70	30 K? On polyester	

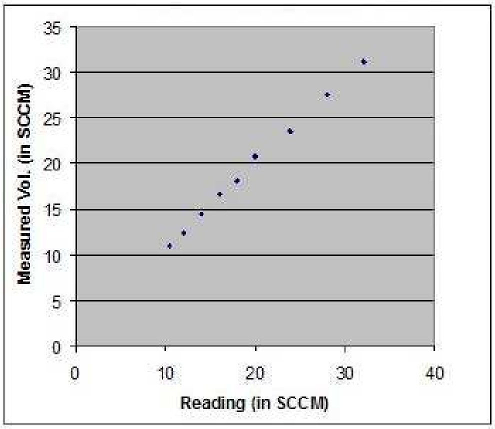
Figure 5: Optimisation of painting parameters for carbo paste

application technique. So far, we have painted the electrode surfaces manually, using auto spray guns. This method has several apparent disadvantages, which will result in variations in the final surface resistivity obtained across the entire area of the glass. More over, this technique is inherently slow and not suitable for large scale production which ICAL experiment needs. We have therefore started designing paint automation techniques and developed prototype robotic machines (Fig. 4) for the purpose with help of local industry[26].

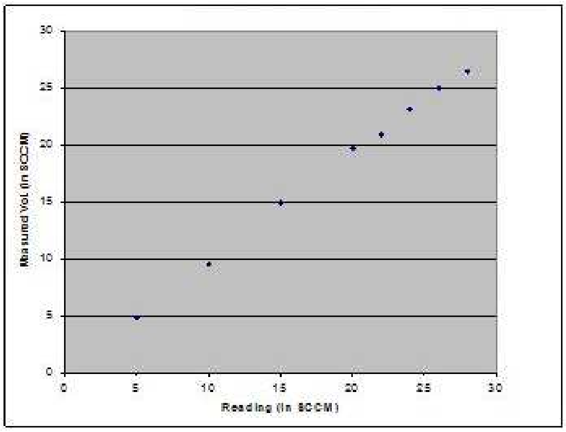
Figure 6: Various steps involved in screen printing technique

Apart from the technique mentioned above, we are also exploring 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 whichcan be stuck on the glass electrode surfaces. This method however has required us to use another type of paint called carbo paste DC-1000M and DC-20 manufactured by M/s Dozen Tech, Korea. This ink is of higher viscosity (350-400 centipoises) and higher drying time compared to the paint that we use for spraying, else the ink would dry out on the screen mess before it is transferred to the substrate film. We have developed this screen printing technique as well as optimized various process parameters (Fig. 5) such as individual fractions of the constituent inks, screen printing mess density, infrared radiation curing procedure and so son with help of a local industry and obtained good results on large area polyester as well as on glass sheets. The paint quality on the glass sheets in particular were exceedingly good, while we are monitoring the surface resistivity for its longterm stability. We show various steps involved in the screen printing technique in Fig. 6.

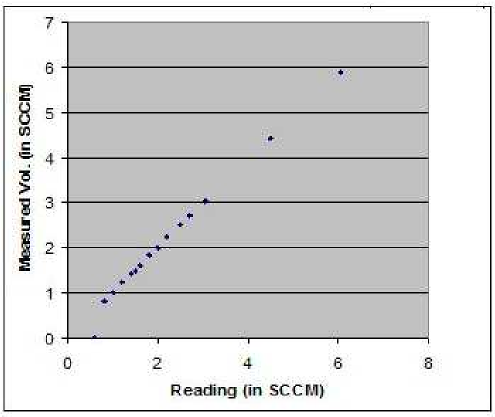
6 Calibration and precision studies of the gas system



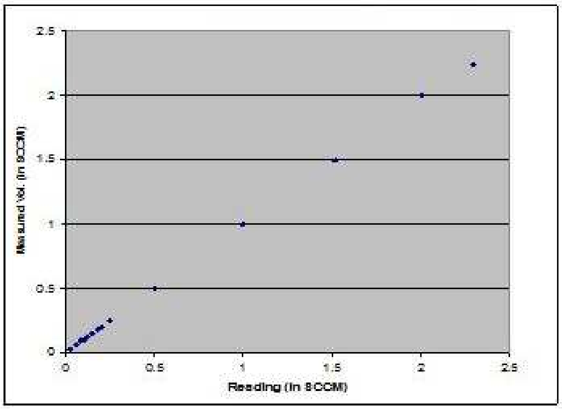
(a) Argon



(b) Freon (R134a)



(c) Iso-butane



(d) SF_6

Figure 7: Calibration plots of various MFCs

We had designed and developed a new type of sophisticated 16-channel gas mixing and distribution system. This system will be used for flowing gas to the ICAL prototype detector employing

12 RPCs. It is capable of accurately measuring and control mixing of four input gases viz. Argon, Freon(134a), Isobutane and SF_6 in the required proportion using Mass Flow Controllers (MFCs). The mixed gas flows in each of the output channels are maintained constant by using 300μm stainless steel capillaries, serving as gas flow resistors. Gas flow at every stage of the system is achieved through the use of electrically or pneumatically operated switches or valves. The system is equipped with a host of sensors and monitoring devices and appropriate displays of various crucial operating and quality control parameters. We have reported the design, construction and commissioning details of this system earlier[16].

This system is functioning as per its designed specifications and is already playing a major role in all our precise measurements of the RPC detector performance. But, as we moved ourselves into precision measurements' regime as far as the RPC detectors are concerned, we have also decided to calibrate various aspects of the gas system thoroughly. One of the important tasks was precise calibration of MFCs which control the individual gas flows into the mixing unit of the system. This is even more crucial in case of SF_6 gas as its volume in the mixture is hardly a fraction of a percent, but even minute variations in the flow of this gas affect the chamber characteristics drastically.

MFCs are designed and calibrated to control a specific type of gas at a designed range of flow rates. Normally, the rating on MFCs is the one that corresponds to the flow of nitrogen gas, and hence, calibrating the MFCs for the particular gas which its controls in the system is a prerequisite. The input control as well as the output monitor signals of the MFCs range from 0 to 5 volts dc and the flow through them is linearly proportional to these voltages. All the MFCs employed in our gas mixing system are calibrated by water downward displacement method. The MFC under calibration is first set to a precise control voltage. The gas flowing through this MFC at this setting is collected in an inverted graduated jar immersed in water from one known level to other known level together with the time taken for the same. The ratio of level difference upon time gives the average flow rate during calibration period. The control signal is then set to a different voltage, the above procedure is repeated and the time as well as the level differences are recorded. This procedure is repeated for many values of the MFC control signals. Flow rates thus calculated and the corresponding control signals are plotted to obtain the calibration curve for the gas under test. All the MFCs are calibrated using this procedure and the calibration results are shown in Fig. 7.

We are also developed another technique to cross-calibrate the above procedure. This involves sending the gas through a long horizontally placed glass pipe of accurately known inner diameter. Close to the tube end where the gas is let in, a small hole is made on the wall of the tube through which a drop of water is introduced before letting the gas start flowing. The gas pushes the water drop horizontally and the time taken the drop to travel a distance depends on the flow rate of the input gas. Several readings of distance the drop travelled and the time it took for the same are recorded and plotted. Similar to the above scheme, the measurements are repeated for different control signal settings of the MFC and also for different MFCs. We have found and excellent agreement of data obtained from the above mentioned techniques. The gas system has thus been very accurately calibrated.

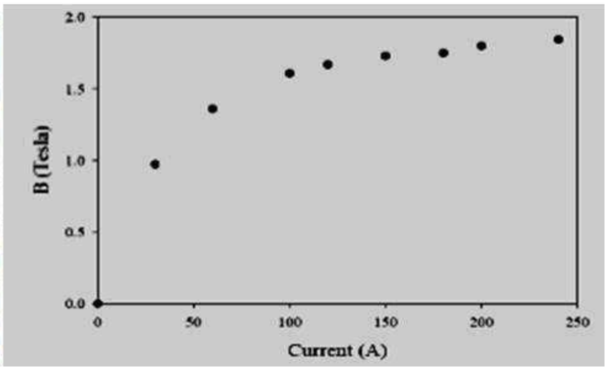
7 Design and construction of prototype detector magnet

A prototype 35 ton ICAL detector is being setup over ground to track cosmic ray muons. Experience with the prototype will be highly useful in planning for the much bigger ICAL detector. This prototype will provide an active detector volume of about 1m^3.

The geometry and structure of INO magnet is largely fixed by the concept of ICAL detector. It provides target nucleons for neutrino interactions and also acts as a medium in which secondary charged particles can be separated on the basis of their magnetic rigidity. Since the prototype detector is designed to detect muons, only the second function of the magnet is required. However, the overall design of prototype magnet was kept as close to the conceived design of the full scale INO magnet as possible. The prototype magnet is of 13 layers, housing 12 RPCs of 1m^2 in area between them.

Design optimisation, simulation and evaluation of the magnet as well as post-simulation data analysis were carried out using the Finite Element Method (FEM) based software package called Magnet. The design variables considered were iron plate thickness, gap between two layers, material used for magnetic path, iron to copper ratio, coil location and dimensions of the magnetic circuit. For the idealised magnet design, a figure of 2500 Amp-turns was expected to provide a field strength of about 1 Tesla in the iron plates.

(a) Fully assembled magnet



(b) B-H characteristics of the magnet

Figure 8: ICAL prototype detector magnet

The iron plates necessary for this work were obtained from the low carbon iron blocks of a old MHD magnet, whose thickness was 50 mm (-4mm +1mm). Gas cutting was used to obtain pieces that were then joined by tack welding to form a T and a C shaped plates. A single magnet layer was made by joining a T and a C plate. The gap left in between along the leg of T plate is used for locating the coils which are slipped in before joining T and C plates. Spacers made out of stainless steel were welded at appropriate locations on the bottom surface of T and C plates to ensure a uniform gap of 50 mm (+3mm -0 mm) between any two layers of iron plates. Finally to even out the loading of the magnet on the floor, a stainless steel tray filled with cement was designed to provide the base for the magnet. Four sets of coils of 5 turns each were made from electrolytic copper conductor tubing that has a central bore for flowing low conductivity water used for cooling. The power supply for the magnet coils is a thyristor controlled three phase low voltage constant current type and has a stabilized reference to regulate the current.

At 2500 and 3750 Amp-turns, the magnetic field B in the central portion of the magnet was measured to be 0.8 and 1.2 Tesla respectively. The uniformity was seen to be in the range of 5% and reduces as we move to higher fields close to the saturation value. While Fig. 8a is a picture of the fully assembled magnet, in Fig. 8b, we show the B-H characteristics of this magnet. The magnet is now fully commissioned at VECC.

8 Design and construction of prototype detector stack

It was proposed that we build a prototype of the magnetised iron calorimeter and study cosmic ray muons using the same, in order to understand and estimate performance of the final ICAL detector. This prototype detector will also be used to test the results obtained from the physics and detector simulation studies that are currently underway as well as will provide some measured data back to the simulation group. Design and construction of the magnet used for this detector is reported above.

The detector stack is comprised of 12 layers of RPCs each of $100 \times 100\text{cm}^2$ in area. The pickup strips are fabricated using the honeycomb panels which we had developed and reported earlier. The panels are placed orthogonal to each other and on either side of the RPC gas gap. The panels also provide the mechanical support to the RPC. We pick up the signals both on the anode side (negative polarity signals) as well as on the cathode side (positive polarity signals) of the RPC. In all there are 64 electronic channels to be readout - 32 on either side. We apply about 9.8KV high voltage across the RPC in the differential supply configuration. We have fabricated a suitable stand to house these chambers and present a detector stack structure with built in flexibility. While the input gas lines one per chamber are routed from the gas mixing and distribution system, the exhaust gas from the RPCs is collected individually through output bubbles into a manifold, before venting it to the atmosphere. Bleeder bubblers are mounted on the RPC gas input channels for protecting the chamber in case of high pressure built up on the gas line due to blockages etc.

Fig. 9 shows this arrangement as a schematic on one side of the stack. Also shown in the schematic is the arrangement of a scintillator paddle based cosmic ray muon telescope. A combination of several wide and very narrow paddles are arranged and geometrically aligned to define an aperture for vertically going muons through a single RPC strip traversing all the 12 layers of RPCs. Veto paddles are used to make sure that we reject all the tracks which also intercept the adjacent strips. Shown in Fig. 10 is the picture of the ICAL prototype detector stack in operation.

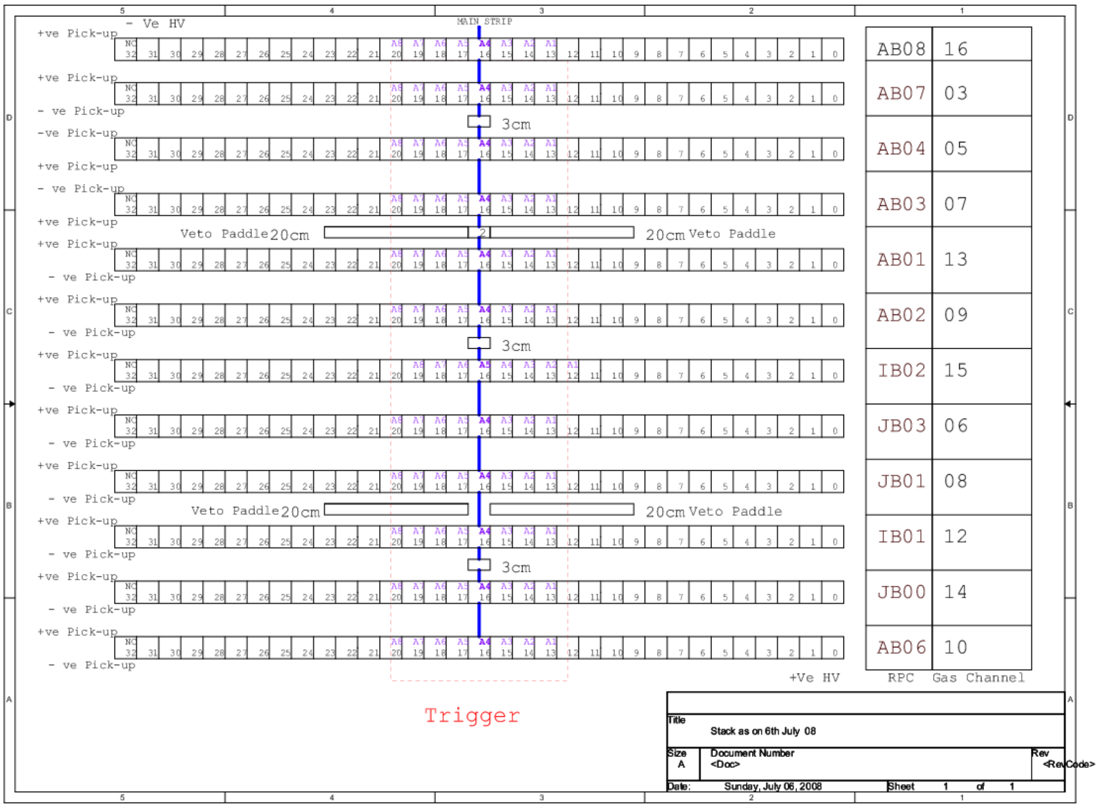


Figure 9: Schematic of the ICAL prototype detector stack

9 Electronics, trigger, DAQ and monitoring systems

As mentioned above, 64 data channels are to be readout from each of the 12 RPCs amounting to a total of 768 channels. Role of the data acquisition system then is to generate the trigger, 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 trigger. Monitoring the stability of the detector as well as laboratory ambient parameters such as temperature, relative humidity and barometric pressure, are the other important tasks of the on-line data acquisition system.

The signal readout chain essentially consists of a front-end fast high gain HMC based preamplifier and low level threshold discriminator followed by the digital front-end. The digital front-end built around a couple of CPLD chips handles important tasks of latching the strip hit pattern on master trigger as well as serially transferring the data to back-end. It is also here that the pre-trigger signals are generated, which are used by the back-end trigger module built using combinatorial circuits and produces 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 timing data is acquired using the commercial TDC

Figure 10: ICAL prototype detector stack in operation

modules. The data acquisition is done using a CAMAC backend, 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 done as a cyclic background job using the scaler module in the back-end. Monitoring of ambient laboratory parameters such as temperature, relative humidity and barometric pressure along with important operating parameters of the RPCs such as high voltage and current is also routinely done and made available on-line on web. Shown in Fig. 11 is a schematic of the data acquisition system for the INO prototype detector.

All the electronics, trigger and data acquisition systems required for the ICAL prototype detector were designed, fabricated, integrated and commissioned this year. The entire stack along with the DAQ systems is in uninterrupted operation for the past several months without any problem and collecting valuable data. While, we have reported earlier the entire design, construction and commissioning of most of the above systems, we wish to however report about

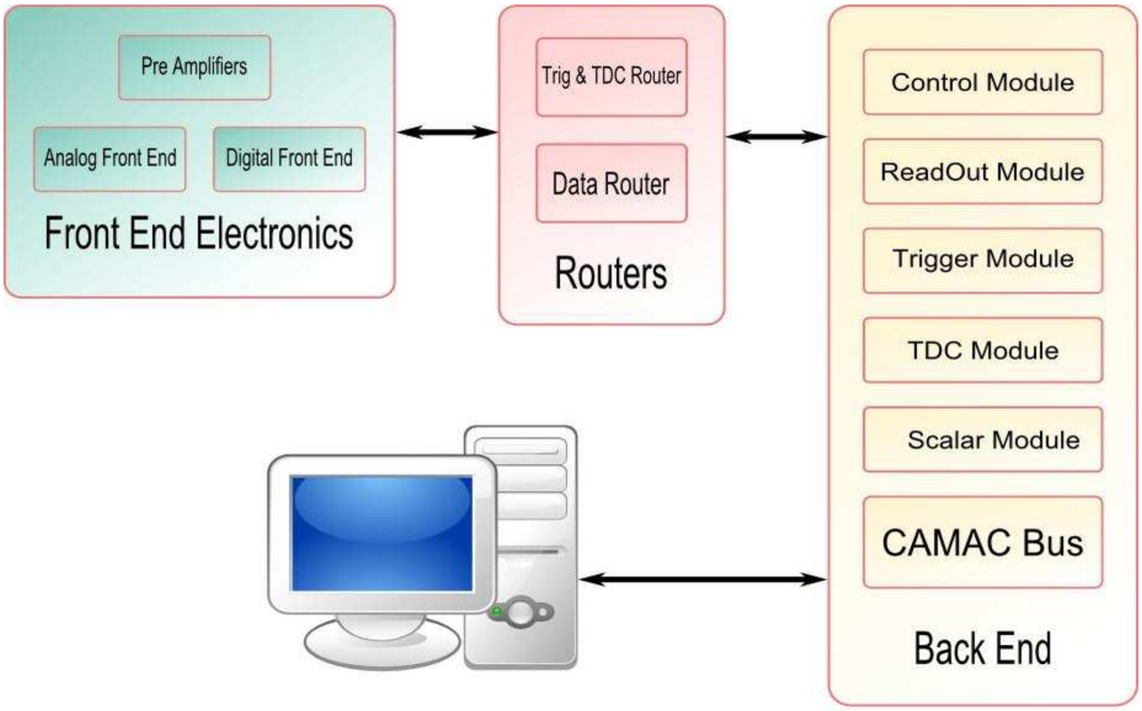


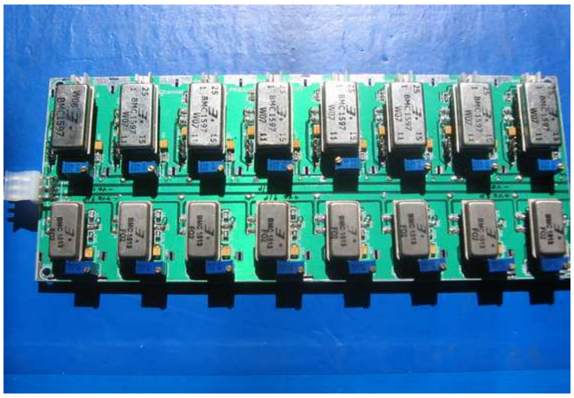
Figure 11: Schematic of the DAQ system for the ICAL prototype detector

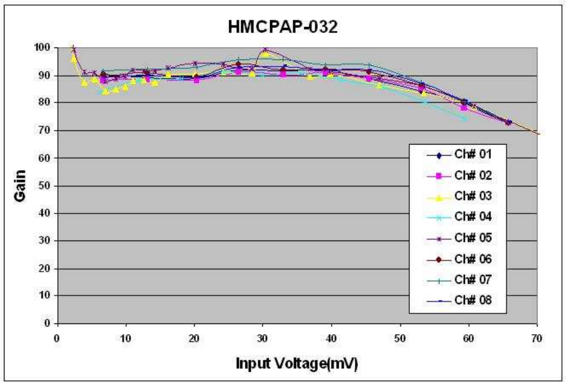
some of the important work that was carried out during the past year in this regard.

In the avalanche mode of operation, in which the INO collaboration chose to run the RPCs for ICAL, the average charges produced for a minimum ionising particles are about a few pico coulombs, which is a factor of 50 lower compared to that in the high gain streamer mode. Hence, there is a need for a high speed, low noise preamplification for the RPC strip signals before it could be processed by the front-end electronics. We have designed and developed two versions of these preamplifiers as HMC packages, both with a gain of 10. Two such stages were connected in cascade to achieve the required overall gain. We have designed 8 channel preamplifier boards using the cascaded configuration and fabricated a large number of these boards. We have extensively tested all these boards before installing them in the detector stack. All the boards have shown excellent performance matching to the designed parameters. Shown in Fig. 12a is a picture of an amplifier board and in Fig. 12b is its gain characteristics.

10 Analysis of ICAL prototype detector stack data

We have developed a sophisticated ROOT based software package to analyse the event, monitor and trigger data collected by the on-line DAQ system of the prototype detector stack. In case of event data, the package interactively displays event tracks and produces a consolidated run summary sheet in which all the extracted RPC characteristics as well as the operating param-





(a) 8-channel preamplifier board (b) Gain characteristics of a preamplifier

Figure 12: Preamplifier for the ICAL prototype detector

eters are given. Along with, all the hit, charge and TDC distributions as well as scatter plots of parameters of interest are also produced as ROOT histograms as well as plots. A number of important studies on the RPC pulse profiles, chamber efficiency plateau characteristics, absolute and relative time resolutions, time profiles of various parameters of interest and validation of various front-end electronics designs were done already using this software package. The package utilises a highly segmented input configuration file through which various functions and user interfaces of the package can be effectively controlled.

Shown in Fig. 13 is an interesting cosmic ray muon track as seen in two views, which is produced by the analysis programme. Some layers on the positive signal side view are missing the hits as these were not equipped with front-end preamplifiers at that time.

One of the most important capability of the RPC that we would like to characterise is its timing resolution. This is because it is this capability of this detector, 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 from bottom to the top. This is an important measurement in the context of atmospheric neutrino studies. Shown in the Fig. 14 are the time resolution (TDC) plots of the RPCs in the prototype detector stack. The timing data is measured between the cosmic ray muon trigger generated by multiple scintillator paddle based telescope and the time of the associated hit in the RPC. As can be seen from the distribution fit parameters, the average time resolutions recorded are in the range of 2nSecs.

Shown in Fig. 15 are the relative time resolution plots of individual RPCs for the same data. In this case, we choose one of the RPCs in the stack as a reference and compute the relative timing between the reference RPC and individual RPCs. So, the distributions are essentially of the time differences between the two RPCs. As expected these relative time resolution plots are much narrower and produce time resolutions of less than 1.5nSec. This shows that the intrinsic time resolutions of the RPCs are better than that of scintillation detectors. Summary of these results is shown in Table 1.

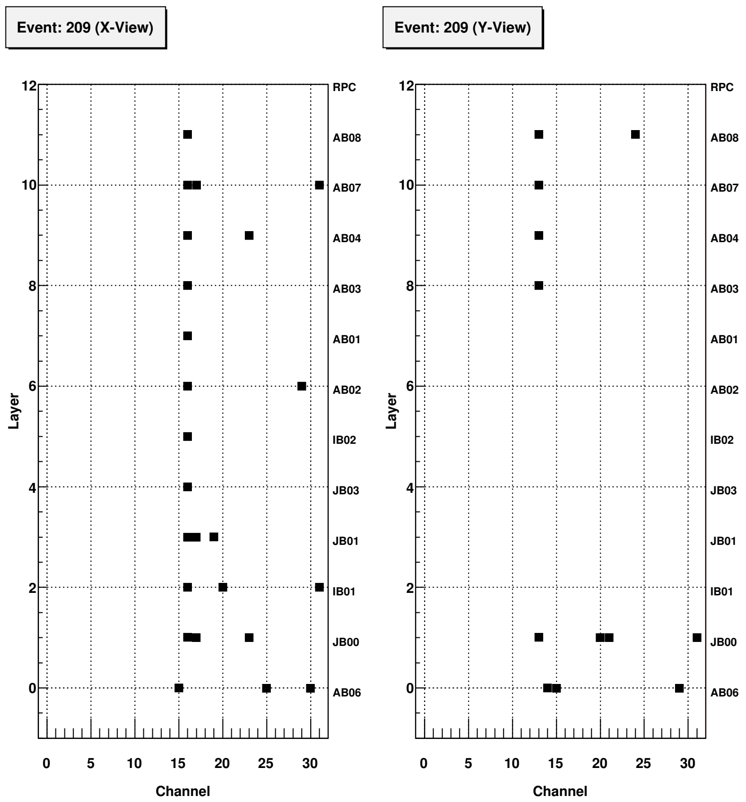


Figure 13: A cosmic ray muon track seen in the prototype detector stack

RPC Id	HV(KV)	Mean(nS)	Sigma(nS)	RelMean(nS)	RelSigma(nS)
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

Table 1: Summary of time resolution measurements

Shown in Fig. 16 is a time profile of efficiency of a typical RPC for cosmic ray muon detection.

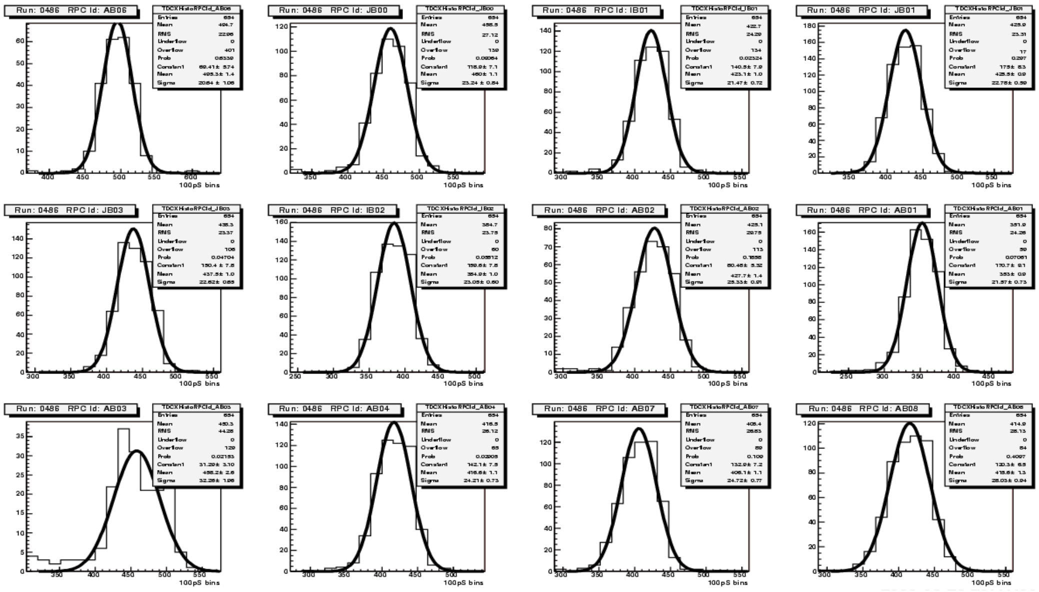


Figure 14: Absolute time resolution plots of prototype detector RPCs

In fact, we routinely characterise every newly fabricated RPC for its cosmic ray muon detection efficiency as a function of the high voltage. We fix the operating high voltage for that RPC corresponding to efficiency plateau which are typically above 90%. Efficiency plateau is the region where the efficiency is constant over a wide range of operating high voltage. The purpose of monitoring this parameter as a function of time is to ensure that this value remains uniform throughout the run.

The analysis program also builds strip hit maps for all the RPCs in the detector stack for a given run. This plot helps to ascertain ourselves that the entire area of the chamber is active and sensitive to the cosmic ray muons and that there are no *hot* zones. One such plot is shown in Fig. 17.

While the data on trigger is acquired, the on-line data acquisition system also monitors and records individual strip rates. This information is invaluable as it indicates the stability of the chamber under operation. The analysis software also handles this data and provides time profiles of this data as well as the rate distributions over a period of time. Shown in Fig. 18 are time profiles of individual counting rates for a set of strips of an RPC. These rate profiles of a stable RPC detector essentially indicate day-night variations, reflecting the systematic changesin the gas composition modulated by temperature variations during 24 hours. Similarly, rates of various paddles forming the cosmic ray trigger as well as some of the pre-trigger rates are also monitored using a VME based data acquisition system. All these rates are handled by the analysis software and produces run summary sheets as well as time profile and distribution

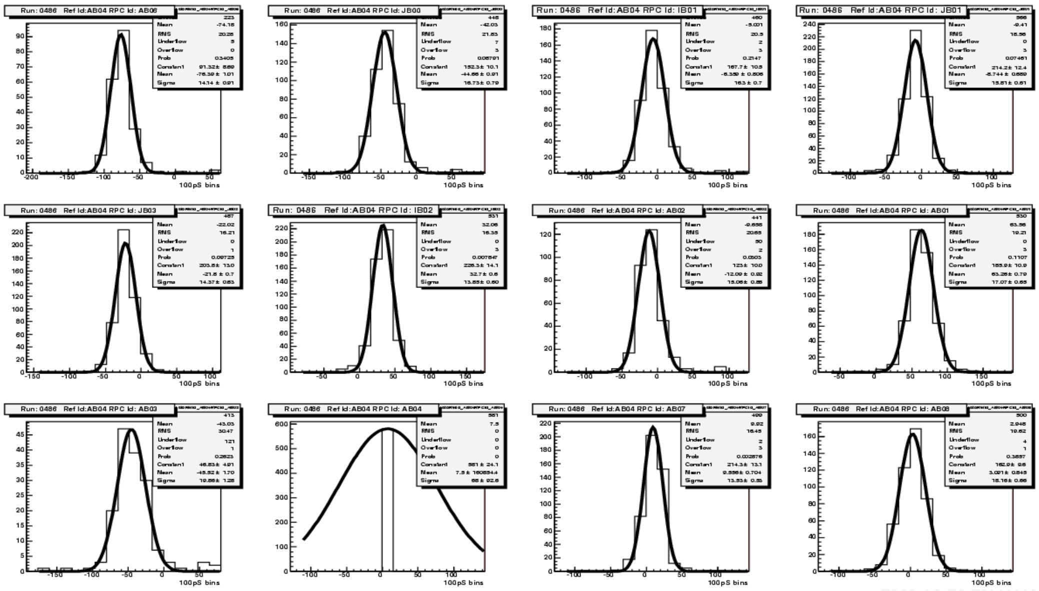


Figure 15: Absolute time resolution plots of prototype detector RPCs

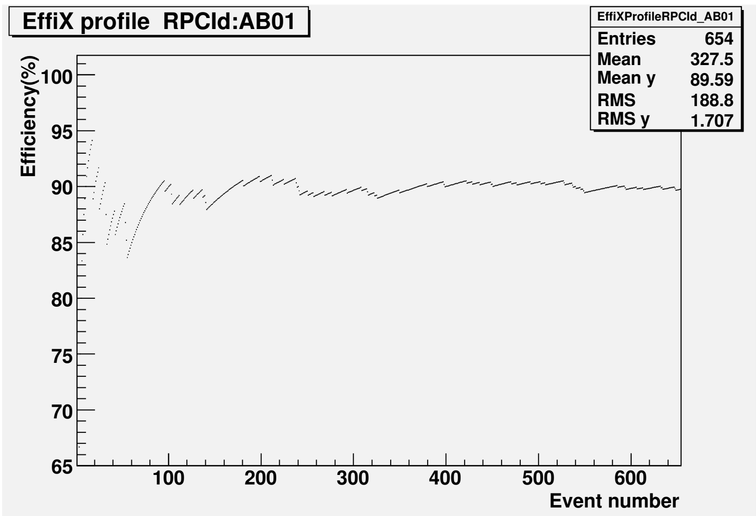


Figure 16: Efficiency profile of a RPC in the detector stack

plots of this data for ready reference.

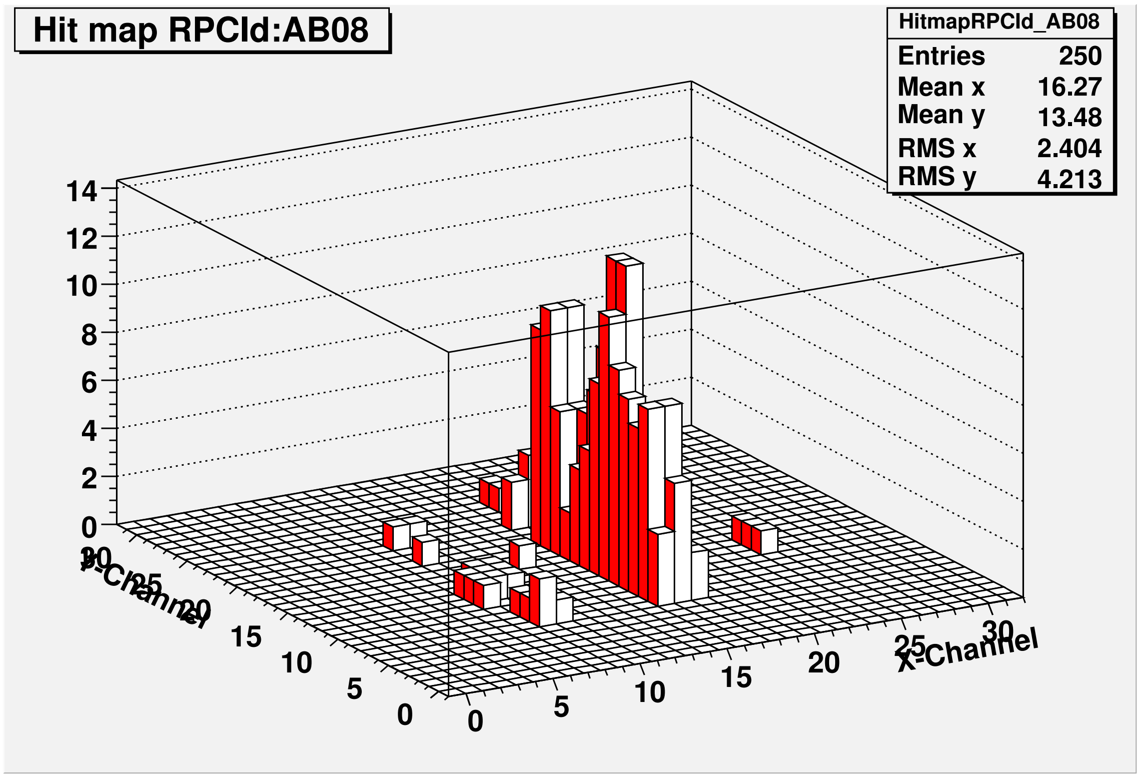


Figure 17: Strip hit map lego of a RPC in the detector stack

11 Study of RPC cluster size

The chamber cluster size, 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. Usually a chamber is accepted if the cluster size is below 3 strips at the knee of the efficiency plateau.

The track impact point on the chamber under test can be also determined and the distance to the nearest cluster center can be evaluated. The root mean square of the residual distribution is an estimation of the chamber spatial resolution. A chamber is considered efficient if the reconstructed muon trajectories match the fired strip within a distance of 3.

RPC	AB01	AB02	AB03	AB04	AB06	AB07	AB08	IB01	IB02	JB00	JB01	JB03
Size	1.1	2.3	2.2	2.3	4.0	2.4	1.9	2.2	1.1	1.6	3.0	1.1

Table 2: Cluster sizes of RPCs in the stack

Shown in Fig. 19 is the cluster size distributions of all the RPCs under test in the prototype

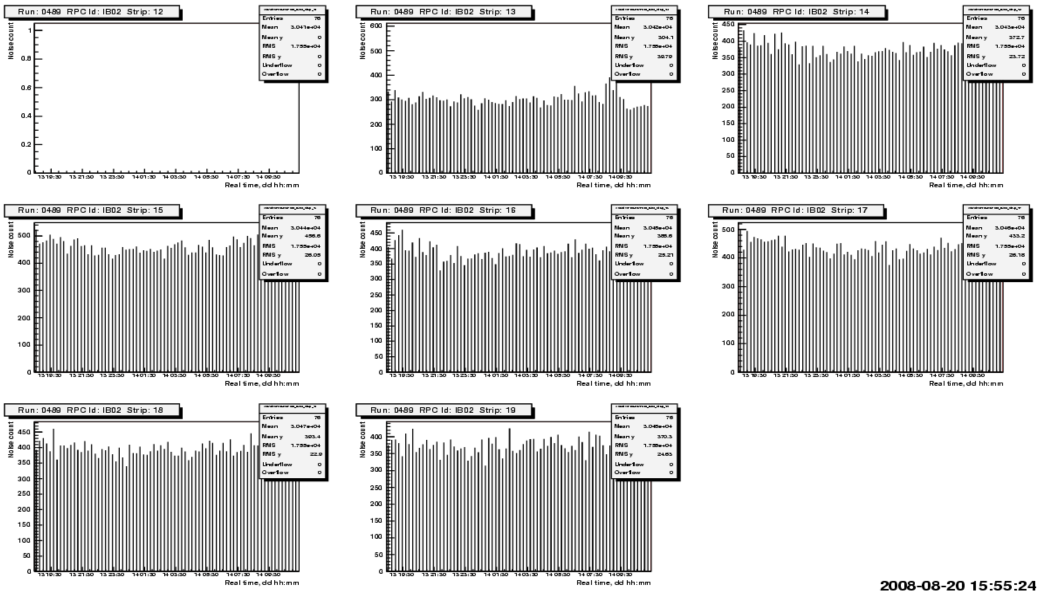


Figure 18: Strip rates' profiles of RPCs in the detector stack

detector stack, using the negative polarity pickup signal data. Arithmetic means of these distributions is given in the Table 2. The track impact points of all the RPCs in the stack are expected to be the same because the trigger is formed by using a set of narrow scintillator paddles placed on vertically aligned single RPC strips.

12 Future work plan

We have made a substantial progress on designing, building and characterising the large area RPC detectors using the infrastructure which is built completely in house and bringing the detector technology close to mass production of the detectors for the ICAL detector. We have also designed, built and commissioned RPC detectors as well as electronics and data acquisition systems for the ICAL prototype detector during the current year. We plan to integrate various components of the prototype detector in the coming months at VECC, Kolkata. This detector will validate the RPC devices as well as the detection technique which is planned for ICAL detector. It will also give useful data on using the RPC devices in high magnetic field, which is unique in case of ICAL detector. Developing RPC detector technology in the country is a major milestone for the INO experimental programme.

Subject to the approval of our Research Progress Committee (RPC) and the Institute, we wish to conclude and summarise the work and start writing up the thesis. We will essentially con-

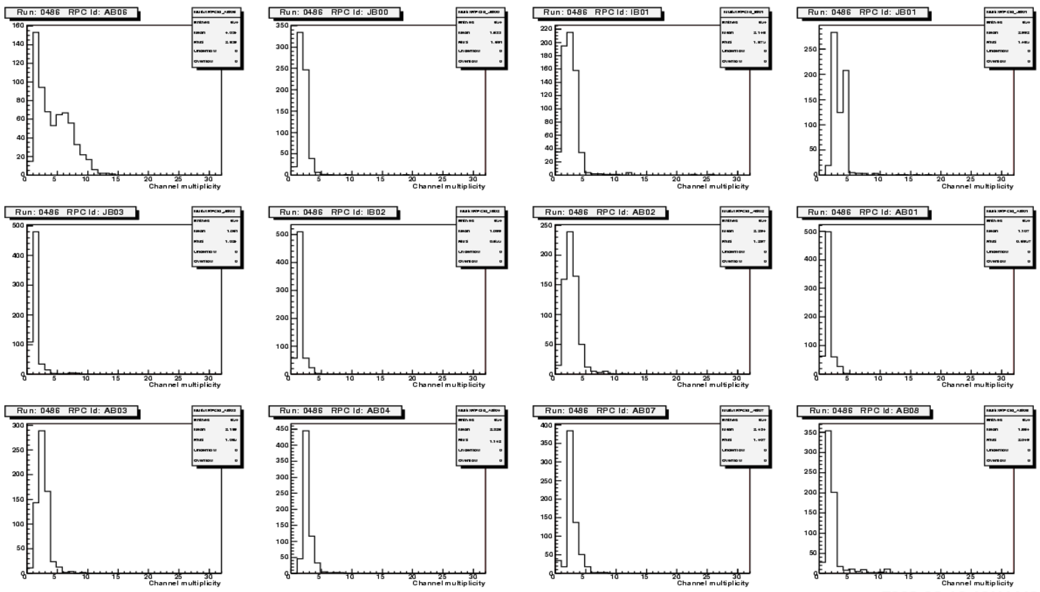


Figure 19: Cluster size distributions of RPCs in the stack

tinue our R&D programme beyond the scope of this thesis, especially extending into the areas of detector simulation, ICAL specific RPC detector design optimisation and other precision performance characterisation studies.

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I am grateful to my Ph.D supervisors, Prof Raghava Varma and Prof Naba Mondal as well as Prof Basant Nandi and Prof Uma Sankar for their constant encouragement, guidance and support. I also wish to acknowledge contributions from my INO detector development team colleagues, Manas Bhuyan, Satyajit Jena, S.R.Joshi, Shekhar Lahamge, S.D.Kalmani, P.Nagaraj, L.V.Reddy, Asmita Redij, Mandar Saraf, R.R.Shinde, Piyush Verma and the team mechanics in particular.

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[26] The INO Collaboration, Development of conductive coated polyester film as RPC electrodes using screen printing, RPC2007contribution, NIM A preprint

A Presentations and papers on my work

I have made the following technical presentations on my work at various conferences, symposia and meetings mentioned below. Some of this work is in the process of appearing as publications.

1. Development of glass Resistive Plate Chambers for INO experiment, Proceedings of RPC2007, Nuclear Instruments and Methods A, In press
2. INO prototype detector and data acquisition system, Proceedings of RPC2007, Nuclear Instruments and Methods A, In press
3. Development of conductive coated polyester film as RPC electrodes using screen printing, Proceedings of RPC2007, Nuclear Instruments and Methods A, In press
4. On-line gas mixing and multi-channel distribution system, Proceedings of RPC2007, Nuclear Instruments and Methods A, In press
5. RPC exhaust gas recovery by open loop method, Proceedings of RPC2007, Nuclear Instruments and Methods A, In press
6. Development of glass Resistive Plate Chambers for INO, Proceedings of International Conference on High Energy Physics, University of Philadelphia, July 29 - August 5, 2008
7. Development and characterisation of large area glass Resistive Plate Chambers for the ICAL detector at INO, Proceedings of Nuclear Physics Symposium, Sambalpur University, December 11-15, 2007
8. Electronics and data acquisition system for prototype INO-ICAL detector, Proceedings of Nuclear Physics Symposium, Sambalpur University, December 11-15, 2007
9. Development of Resistive Plate Chambers for INO ICAL detector, Invited talk at University of Roma Tor Vergata, November 2, 2007
10. Electronics for the INO ICAL detector, Presentation at KEK, Japan, November 27, 2007
11. Commissioning of ICAL prototype detector electronics, Presentation at INO Collaboration meeting, BARC, April 13-14, 2008
12. Electronics, trigger and data acquisition systems for the INO ICAL detector, Presentation at INO Collaboration meeting, BARC, April 13-14, 2008
13. Possible schemes for INO-ICAL electronics, Presentation at INO Electronics Meeting, TIFR, September 21, 2007
14. The joy and challenge of doing experimental particle physics, CBS Colloquium, August 12, 2008