Report of work done at TIFR and BARC,

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This is a report of work done in the TIFR C-217 RPC lab, along with extensive help and contributions from Sarika Bhide, P R Joseph, Devdatta Majumder, S D Kalmani, G K Padmashree, Mandar Saraf, Anirban Saha, S Chavan, B Satyanarayana, Ravindra Shinde, and P. Verma (I hope I haven't left out anyone). A small part of the work was done in the BARC RPC lab with V M Datar, L M Pant, and Vineet (forgot his surname). So this is essentially a report of a learning experience and I thank all those from whom I learned this stuff and all those (many not listed here) who made my visit so enjoyable. It goes without saying that all mistakes in this report are mine alone. Also, I had two breaks while writing this report, one to go to Ooty/Masinagudi and the other to go to Manali! So more errors may have crept in due to natural memory loss.

I assume that anyone reading this document does not need a section on motivation and introduction. In the next few sections, I will set out details of the things I learned, including,

- How to make an RPC,
- Some (very few actually) highlights of the gas mixing unit,
- How to measure some RPC characteristics, including surface resistivity and I-V characteristics,
- The electronics associated with testing the RPC efficiency,
- Some RPC studies including studies of the pulse shape, etc., the temperature dependence of efficiency, and some preliminary studies of cross-talk when the RPC was run in the avalanche mode,
- Some very early studies of RPC in the streamer mode (at BARC).

Finally, I will outline what I think are the open issues and possible directions of future work.

1 How to make an RPC

We made 4 small RPCs (3 of them 30×30 cm^2 and one of them 29×29 cm^2) and four large RPCs of size 1×1 m^2 are still being made as I write.

Glass cutting and cleaning : All glass used in this round was Japanese 2 mm glass. The larger glass comes in the correct 1×1 m^2 size, while the smaller ones were cut to size using a diamond cutter (while I watched). The four edges were then cut off about 3 cm or so from the edge to make an octagonal shaped piece. A jig of just the right dimensions is used to make a correct 45° angle, as shown in Fig. 1.

The glass was thoroughly cleaned with alcohol (propan-2-ol) on both sides. It was then washed with labolene and distilled water (the net suggests a 0.1% solution) behind closed doors in the men's toilet! The water is thoroughly wiped off at once and the glass is once again cleaned with alcohol. Gloves and large amounts of tissue paper are a must. Once the glass is cleaned, the "inner" surfaces are matched together with some thermocol in between (*) and the edges taped over with masking tape, about 1.5–2 cm being taped off or masked on each side. This will prevent the conductive paint from being coated right up to the edge of the glass (otherwise it will short when high voltage is applied) and will preserve the cleanliness of the inner surfaces. (* Note: the thermocol may not really be clean; perhaps we should put a sheet of mylar in-between. This is something we need to think about). The glass is now ready to be glued together with the edge spacers.

Glueing of glass : Actually the smaller glasses were glued and then graphite-coated while the larger ones were coated and then glued. The reason for this is simple: the smaller RPCs were glued and coated in-house; the larger ones were coated outside and there could be a risk of gas-leaks developing if the RPC was already glued, during transport and handling.

The glue used was a 3M Scotch-weld epoxy adhesive in a duo-pak cartridge and was applied using the branded 3M EPX applicator. For the small RPCs, glue was applied at 4 points equally spaced on the inside of an RPC and 1-cm buttons (with three holes, as a point of interest, unlike the usual 2- or 4-holed shirt buttons, but otherwise completely similar) were pressed on to the glue. A little glue was placed on the top surface and the upper glass lowered on it. The glass was pressed into place.

The edge-spacers : These are designed in sections: a straight piece, and an angle or corner piece. This is because the edges of the glass are cut with a jig so that there is room for the input and output gas tubes. The corner piece (top view shown in Fig. 1) has two wedges on either side that slot neatly into holes in the straight sections. It also contains the gas inlet/outlet pipes into which the gas tube fits. The dotted lines in the figure show the original square edge; note that the entire corner section, including the gas pipe, lies wholly inside, thus decreasing the chance of damage during transport (which can happen if the tubes are protruding out). Every corner has a gas pipe: two to be used as inlets and the other two as outlets.

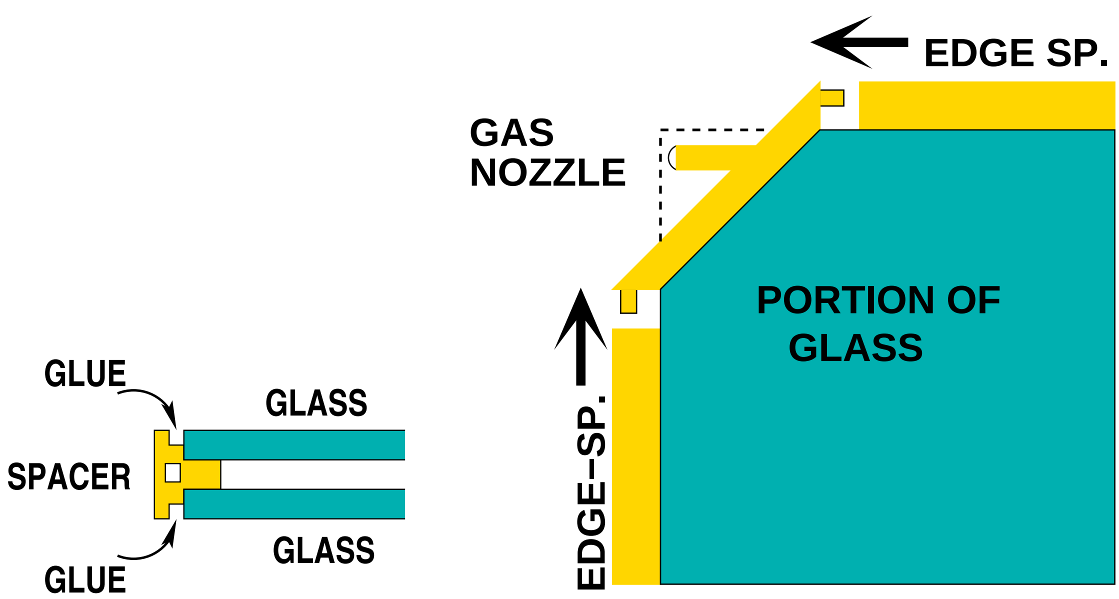

Figure 1: Left: Side view of the spacers, indicating the central gap and position of glass with respect to spacers. Right: Schematic top view of corner piece of edge-spacer, with gas nozzle. The arrows indicate the manner in which the straight edges slot into the corner piece.

The straight edge-spacers are also designed in "steps" so that the glass sits neatly within: see the edge view in Fig. 1. There is a 1 mm gap where the glue can be poured (see figure). The central protrusion is 2 mm, thus supplying the required gap between glass plates. The central hole (shown in white) is where the wedge of the corner spacer fits.

The edge-spacers had already been cut to size (if these are cut and checked before cleaning, they may acquire oil stains which are hard to get rid of; if they are cut and checked after the glass is cleaned, the glass gets dirty again and needs to be recleaned with alcohol, but Padmashree assures me that this is the better alternative. The reason so much is said about cleaning is that Prof Abe insisted that this was the critical part.). The edge spacers were pressed into place on the top side and the whole assembly was weighed down with lead bricks until the glue set (about 6 hours). After this it was turned over and the glue applied on the other side of the edge spacers. The lead bricks were applied again and the whole was left to set. This should preferably be done in as clean an environment as possible.

For the larger glass, more buttons were used and also a vacuum apparatus was used to apply uniform pressure while drying. This whole equipment is in the portacabin near the painting section and I never got to see it in operation, since the portacabin is just about getting ready for use.

Masala for graphite layer : The conductivity of the glass is increased by coating it with conductive paint. Three versions were available. The 4 small glasses were coated with graphite. Here 25 gms of lacquer and 3.4 gm of graphite powder were dissolved in 40 ml thinner and stirred well with an electric blender. If necessary, more thinner can be added to get the right consistency. This much is sufficient to coat both pairs of 4 smaller RPCs, with some left over. The coat was applied using a spray gun by Shri Shette of the automotive section. Unfortunately he also sprayed himself in the eyes with thinner: it appeared to be extremely painful but he assured me that the (burning) feeling would wear off in 4–5 hours.

Once the surface is coated, the masking tape is removed and the resistivity of both surfaces determined using two fixed sizes of copper and brass squares (about 2 and 20 cm square). There should not be too much variation across the glass and also between the two sides. While the TIFR group was aiming for a resistivity in the ball-park of 400 KΩ, Prof Abe of the Belle Collaboration mentioned 1 MΩ or so. Clearly this needs some study.

The RPCs were checked for surface resistivity: apparently, the initial number cannot be trusted since the resistivity is initially higher, decreasing over the next few days and finally settling down to its final value.

One of the smaller RPCs had the right resistivity properties; the resistances of all the other RPCs was too low (less than 200 KΩ). So the graphite coat of three of them was scraped off using acetone and then it was recoated with some conductive paint that Shri Kalmani had brought from Gran Sasso. Here the resistivity was too high (much more than 1 MΩ, so another coat of paint was applied to decrease the resistivity). These have not yet been used. The larger glasses were cleaned as mentioned and sent to Unicoat for painting with special conductive paint developed by Nerolac Paint company. They should be back by now.

Gas leak test : Now the base RPC is ready and it needs to be tested to make sure that no gas leak occurs, especially at the glued joints. Two tests are made (and both in D-423). First, freon gas is flowed through (how sensible, to flow a safe gas for a leak test!) and a sniffer with two levels of sensitivity (I couldn't tell the units) was used to see if there was any obvious leakage. Then, the gas outlets were connected to a manometer while the input gas was turned off and the inlets sealed. The levels of the two sides of the U-tube in the manometer were adjusted to be the same, and a marker put in place. Any gas leak would result in leak of gas into the manometer, with a resultant pressure on one arm of the U-tube; hence the levels of the two sides would be different after some time.

The RPC which had about 400 KΩ resistivity was tested for leaks and was found to be fine. My first RPC (made in collaboration, of course) was past the first post! It was then sent off to BARC for testing in the streamer mode.

High voltage cables : Now the base RPC is ready and it needs to be wired for applying high voltage and picking up the signals as charged particles pass through. The high voltage is applied to the graphite layer by sticking on a copper square (it's like a children's sticker: you peel off the paper and then press the sticky-side down on to the graphite). Leads are then soldered on to the copper. Two sets of connections are made, on the two sides of the glass; either a positive voltage on one side with the other side earthed, or, even better, positive voltage applied to one side and a roughly equal and negative voltage to the other side, using a bi-polar high voltage DC supply, so that both see a(n internal) common ground. The latter is better since each glass surface sees only half the total voltage, thus decreasing the chances of HV leaks. In the smaller RPCs, ordinary leads were used for the HV supply; it appears that the HV can leak through them and give a shock. In the bigger RPCs which are mounted inside an aluminium chamber, there is a proper SHV connector and fat black cables (I don't know if they have a special name) which are leak-proof (I touched and checked!).

One point: I noticed that the CERN sample RPC in BARC had kapton tape stuck over the joints in the edge-spacers; this may have been used to prevent leakage of HV at the glued joints. This is one thing that we have not tested for: while the glued joints are gas-tight, we did not check their HV characteristics. Prof Abe in fact suggested that we should flow air in the RPC and check for leaks in the high voltage (signalled by excessive dark current, as was observed when the temperature went up by just a few degrees when the A/C failed). We should make this test, or at least cover the joints with kapton.

The pick-up strips : The pick-up strips are made from foils of aluminium pasted on both sides of 5 mm thick foam (earlier thicker ones were used), cut to the same dimensions as the RPC surface. The aluminium is scored through in 3 cm widths on the inner sides, with about 1 mm gap. Leads to pick up the signal are soldered on each side; see Fig. 2. The pick-up strips are placed on each side of the glass such that the strips on each side are transverse to each other, thus providing the x- and y-position information for each RPC.

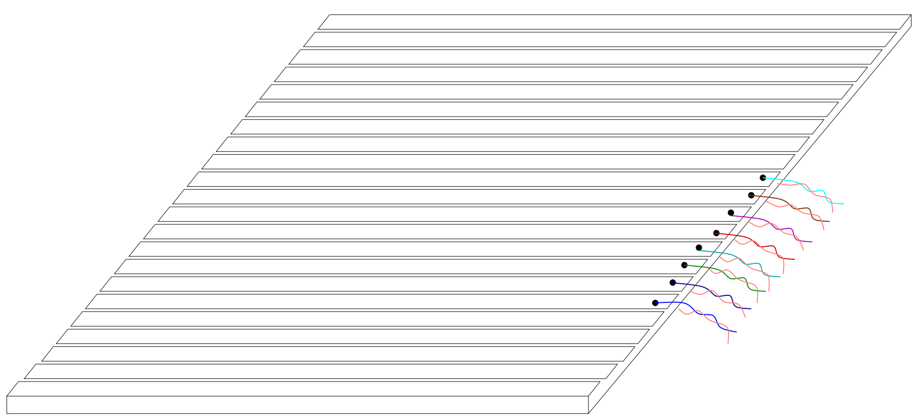

Figure 2: Inner aluminium surface of pick-up strips, showing the grooves spaced 3 cm apart. Each strip has leads connected to it, with the ground end being provided by the outer, unscored side. The aluminium surfaces are glued on to 5 mm thick foam sheets which provide insulation, strength and protection for the glass.

The lead from the strip carries the signal and the one from the unscored alumnium surface is ground. When the RPC sandwich is made, the foam is oriented so that the strips are transverse to each other on each side, thus forming the x- and y-strips. At present, due to shortage of electronics, only 8 strips are connected, per side. The foam with aluminium acts as a transmission line, with impedance of about 100–110 Ω. In future, the plan is to multiplex the output of every eighth strip, and use known delays to readout the strip number; for now, as stated, only 8 strips are connected.

The wires are lead through a 16-pin FRC connector to a patch panel, which converts the signal to one with a standard 50 Ω impedance. The other end of the patch panel has 8 lemo connectors of 50Ω impedance, one for each strip, from which the signal (pulse) from each strip can be measured. In the avalanche mode of operation, signal strengths are typically few mV or less.

Note the the earlier version had a fast preamplifier with constant gain of 10 (actually gave more like 9) sitting on the patch panel. The idea is to amplify the signal close to the signal collection point to minimise amplification of noise or distortion of signal, which happens when the signal is taken through long cables before amplification. However, these fast preamps were giving some problems and so their use was discontinued and a 50 gain amplifier (called HEX amplifier, manufactured by BARC/BEL) mounted on a NIM bin, was used in all these studies for now.

The mylar for insulation : Two layers of 100 micron thick (I may be wrong on this number) mylar were placed on top of the graphite-coated outer layer for electrical insulation. The mylar was held in place with pieces of kaptan tape. Another mylar sheet was kaptan-taped to the pick-up panel before it was laid on the RPC, so that there were three sheets of mylar per side for insulation. Apparently this is the magic number; fewer sheets were not sufficiently insulating. The RPC and pick-up sheets were then taped together with kaptan.

In the bigger RPCs, the whole RPC with pick-up strips was mounted inside an aluminium dabba for electrical shielding and structural support. The smaller RPCs were used as such.

2 The gas mixing unit

I learnt least about this part of RPCs. All the 14 days I was in TIFR, the gas was running in avalanche mode, which meant that the flow rate was 18 sccm (standard cc/minute). Of this, 0.82 sccm was isobutane (4.5%) and the rest was freon. At BARC, the mixture being used was 6–7.5% isobutane, and the rest about equal amounts of argon and freon. More argon gives bigger pulses and we kept trying out different proportions. The flow rate was controlled by a mass flow controller. It is not clear how it is calibrated: for instance, when the temperature changed during A/C failure, the flow rate remained the same, but surely the gas density should have changed. Initially the gas was being fed to the smaller RPC stack in the room as well, but those lines were soon switched off. When only three bigger RPCs were connected (two lines in and two lines out, for uniform flow), a bubble count at the outlet showed that the gas flow through each RPC was indeed remarkably constant. The average bubble rate was 48, 50 and 51 bubbles per minute (averaged over 10 minutes) for RPC JB01, IB01, and JB00. With an estimated bubble size of 5–7 mm, the volume flow per minute is 3–9 cc per RPC, which matches the data of 18 cc per minute through all three RPCs. In passing, Prof Abe suggested that we can check the humidity at the exit point as well; currently, this is metered only at entry. An important point is that the gas records are meticulously maintained by two readings a day: this is essential to check for amount of gas remaining and to change cylinders when required.

3 How to measure RPC characteristics

A high DC voltage was applied across the glass by applying both positive and negative voltage to the two sides. The total voltage across the RPC is thus the sum of the two voltages. In order to determine the I–V characteristics, the voltage is slowly ramped up, and the current values noted when stabilised. It was noticed that the response was linear for low voltages but the current increased non-linearly as the voltage was raised. Also, when a new RPC (JB01) was included in the set-up, it showed extremely high currents for relatively small voltages itself. However, after a day or so, the current came down substantially, and after a couple of weeks, the current was about half a microamp for voltages around 9 KV. The dark current is also extremely sensitive to the temperature and humidity. I don't have the full notes of all this and I hope Anirban and Devdatta will discuss this in detail.

The next step is to study the pulses, and in this study, only the negative pulses from the RPC were studied. This was because of the availability of only negative pulse amplifiers. I thought it would be a simple matter to invert the positive pulse from the anode and then feed it to a negative pulse amplifier, but apparently this is not so straightforward.

The pulses from the RPC are sent to a digital oscilloscope and the pulse shape and heights are studied. Unfortunately, data could be saved only on a floppy, and since a floppy could not be found, no pictures of the pulses are available. I can only say that there were two typical kinds of pulses, the standard *avalanche* pulses with very good timing, very deterministic shape, so that *all* the pulses always occurred at the same time with respect to an external trigger, and another so-called *streamer* pulse. The latter was not a genuine streamer such as is obtained in the streamer mode of operation but has a characteristic large, meandering pulse associated with the initial avalanche. The streamer part occurs about 20 ns or more after the avalanche, as sketched in Fig. 3. While the avalanche pulses are a few mV or less in height, the streamers are 10–20 mV or even larger; the height increases with increase in applied HV.

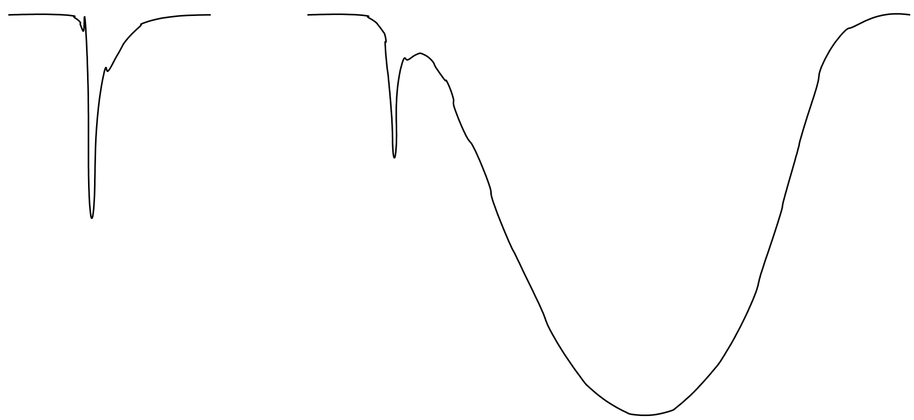

Figure 3: Left: Typical avalanche pulse shape. Right: typical so-called streamer pulse.

4 Efficiency and cross-talk measurements

Now that the RPC has been characterised (and as I said, I haven't plotted the I-V curve here, but I'm sure someone else will send it around; it's been done for every RPC that was ever made), we now go on to its efficiency, which is the heart of the matter. We also made some preliminary measurements on cross-talk, which I will discuss later. The all-important issue of stability, of course, cannot be measured in 2 weeks.

4.1 The experimental set-up

The set-up for measuring the efficiency of the RPCs with respect to 4-fold coincidence from a set of four 1-cm thick scintillator paddles is shown in Fig. 4. The scintillator pulses are fed into a PMT base, with voltage around 1740 V. The four PMTs are at slightly different voltages and so there was a small circuit providing the right voltage to each PMT but I didn't study it closely. The paddles have different widths, with the smallest being 2 cm for Paddle P1 and the next smallest 3 cm for P3. Cosmic ray muons naturally pass through one or more of the paddles. (They are unlikely to be even energetic electrons since there is a lot of glass and aluminium of the RPCs in between). The requirement for a trigger is that all four paddles register a coincidence, which requires the muons to travel vertically downwards within an aperture of 28×2 cm^2.

The ratio of the number of times the RPC also fires within the coincidence window to the total number of such 4-fold coincidences determines the efficiency of that RPC.

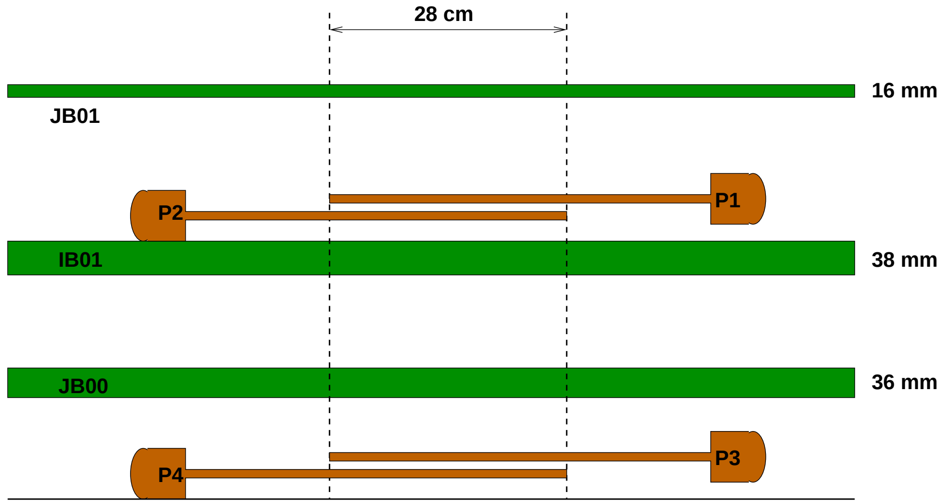

Figure 4: The geometry of the set-up for measuring the RPC efficiency and cross-talk. P1 to P4 are the scintillator paddles arranged such that they have a coincidence geometry of 28×2 cm^2. The three RPCs under test, JB00, JB01 and IB01 are also shown. The scale is roughly 1:0.2.

The electronics for the efficiency measurements :

The raw RPC pulses are fed to an amplifier (gain 50 hex amp, as mentioned, or sometimes, through the fixed 10 gain fast preamp and then through a gain 5 hex amp). See Fig. 5 for a circuit diagram. The output of this is sent to a discriminator, with a threshold set to anywhere between -25 and -40 mV, depending on the type of RPC pulse and the relative noise. Setting this threshold was the most time-consuming part of the whole study: suddenly the noise levels would increase to ± 30 mV and so we would set the threshold at 40 mV, but within an hour the noise would disappear down to ± 2 mV (!!!) and beautifully clean pulses could be seen by the eye down to a few mV, so that we hurriedly reduced the threshold to as far as it would go, which is around -20 mV.

The raw pulses from the PMTs are large and relatively stable (in my opinion, the paddles are rugged beasts) and are directly fed to the discriminator. The threshold really does not matter; it was set to about -25 to -30 mV. A quick comparison of the number of 4-fold to the number of 3-fold (paddles 1, 2, and 3 only) coincidences showed the scintillator efficiencies to be around 90% or better.

The falling edge of the RPC or PMT pulse, when it triggered the discriminator, produced a constant square negative pulse of amplitude 1 V whose width could be adjusted. For most part of the study, the width was set to 60 ns.

The output of the discriminator goes to a scaler counter where the number of pulses are counted. The scaler is gated so that counts are accumulated for typically an hour in each run.

The outputs of the four PMTs are taken as inputs of a 4-fold coincidence logic circuit, whose output is a negative square pulse of width $W_{4-fold} = 60$ mV when all four PMTs register a signal (coincidence circuit). This serves as the trigger. Because of various delays, particularly due to the PMT, the RPC pulses however do not coincide with the timing of this logic circuit. Due to this, the RPC pulses from the HEX amplifier are first taken to an oscilloscope. The 'scope is triggered by the 4-fold coincidence signal. The time delay between the RPC and 4-fold signal is measured.

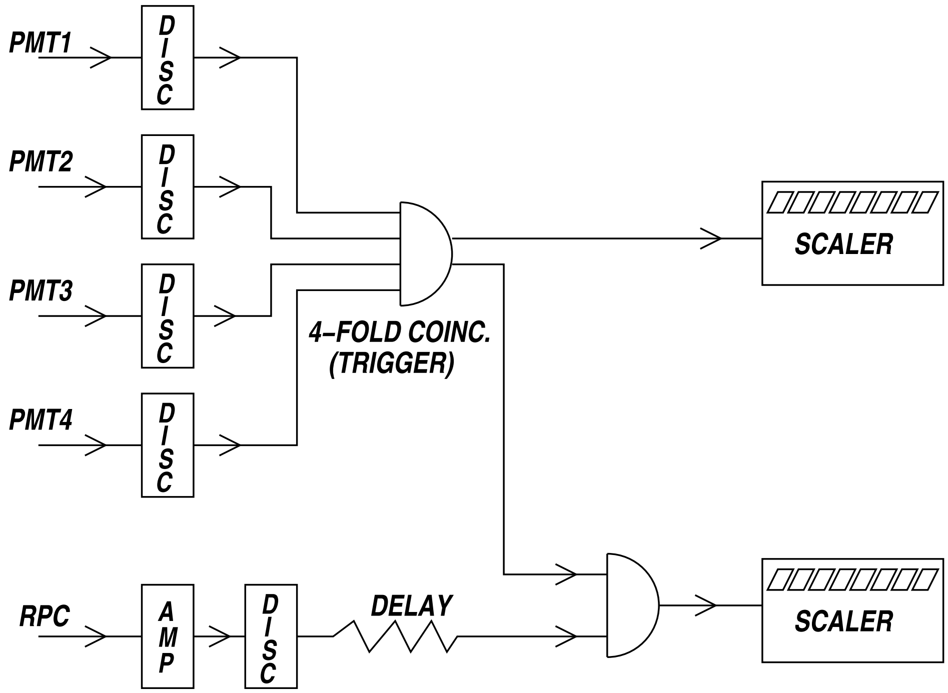

Figure 5: Block circuit diagram for measuring the RPC efficiency. A 4-fold coincidence from 4 PMTs acts as the trigger. The RPC signal was amplified in different ways (see text for details) and then delayed to coincide with the 4-fold coincidence trigger. The counts, both from the 4-fold and the delayed 5-fold coincidence circuits, were counted by gated scalers. The ratio of the number of 5- to the 4-fold coincidences gives the efficiency of the RPC.

Typically, the RPC pulse arrives about 75 ns before the 4-fold coincidence. Delay cables are used such that the RPC pulse from the discriminator reaches a 2-fold coincidence logic circuit roughly at the centre of the 4-fold coincidence window, with the 4-fold coincidence pulse as the other input. The output of this logical unit is sent to a scaler where the 5-fold (delayed) coincidences are counted over a preset time interval. Typical delays of various elements in the circuit are listed in Table 1.

Circuit Element	Delay (ns)
Discriminator	16
Coincidence and/or Logic unit	10
50 Ω cable per metre	5.2

Table 1: Delays caused by different elements of the electronics circuit.

4.2 Results for efficiency of various RPCs

Detailed studies were made of RPC JB01, with some studies on IB01. Unfortunately, no serious measurements could be made with the most stable and long-running JB00 since it was completely wired on to the gain-10 BARC amplifiers which were not working properly (even the raw RPC signal couldn't be accessed). Anirban and Devdatta should have a detailed write-up on this; I am only including it here for completeness, and to discuss the "tasks for the future" (so the present status had better be listed!) Three different scenarios were used:

1. Raw RPC pulses were counted manually, on the oscilloscope (very painful).

2. A gain-50 BARC pre-amplifier was used on the patch panel. Just one such amplifier was

provided for a short time by the BARC electronics division while they tried to figure out the problem with the gain-10 amplifiers.

3. A (tunable gain, but held at 50) HEX amplifier also by BARC on the NIM bin, so that there was a long (2 or 4 m) cable from the RPC to the amplifier, introducing noise and signal distortion.

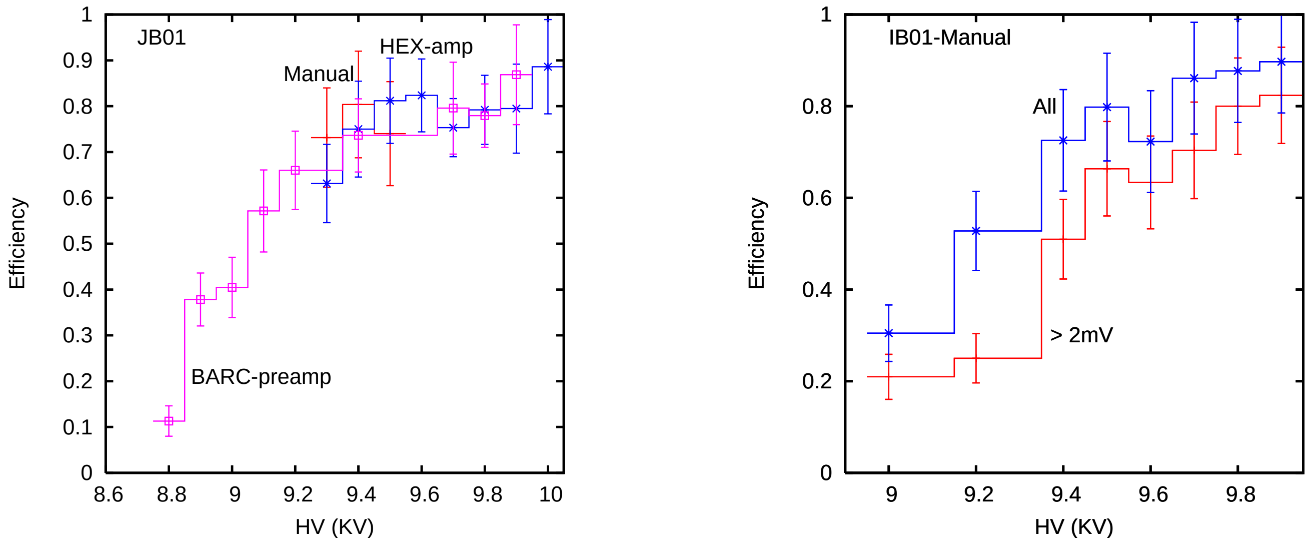

Figure 6: Efficiency as a function of applied high voltage in KV for JB01 (left) and IB01 (right). For JB01, three different sets of measurements were made; see the text for details. For IB01, the lower curve is to be taken; again, see text for details.

The results obtained are shown in Fig. 6 for JB01 and IB01. Note that IB01 has thicker glass plates (3 mm) and so the effective voltage seen is smaller so that relatively higher voltages need to be applied to see decent efficiencies. Also, note that the counting for IB01 was done by directly connecting the 110Ω output of the RPC to the 50Ω input of the oscilloscope. The avalanche pulses were very cleanly visible to the eye, although noise levels were quite high. The lower curve in the figure corresponds to results where the signal (height $>$ 2 mV) is clearly larger than the noise (so that eventually thresholds can be properly set to eliminate triggering on noise). The upper curve is for the entire data set where the eye could discern the pulse but which would have been lost in the noise if the counting had been done electronically. Especially for IB01 it is very clear that cleaning up noise (presumably by proper grounding, or hopefully so!) is crucial to get good efficiencies.

4.3 Temperature dependence of efficiency

Accidentally, it so happened that the A/C to the room failed in the early morning of Apr 27, 2007. While the dark currents drawn by all RPCs were very high, it was not clear whether this was due to increase in temperature or humidity (both were high since this is Mumbai, after all). At that time it was noticed that the efficiency seemed to drop as the A/C was repaired and the room cooled and dried out. At this time the temperature and humidity were falling rapidly and it was not possible to make any conclusions. So, over the week-end, when it was not disturbing the others who work in the room, a set of measurements with increasing temperature was taken. Again, it appeared difficult to maintain both the temperature and humidity at the required values; in fact, this A/C was very efficient in decreasing the humidity. So after three days of hard work, we were left with a lot of data but not taken with much control.

The problems were (a) the temperature did not remain stably at the value set, (b) the humidity could not be separately controlled and kept dropping with time; it also increased depending on the number of people entering the room so the most reliable results were taken on the week-end, and (c) the noise levels were consistently high, about 60 mV ($\pm$30 mV) noise band was *always* there, independent of temperature, so the thresholds had to be set quite high, otherwise the discriminator was always triggering.

After painstakingly going over the data, I found that the most reliable data set was for a HV of 9.4 KV since the RPCs had been left at a fairly low voltage overnight and it always takes time to stabilise at other voltages. For those interested the entire data is in the log-book but this section will only record that part of the data for which the threshold was $V_{th} = -40$ mV and HV = 9.4 KV, for JB01. The results are shown in the graphical table in Fig. 7.

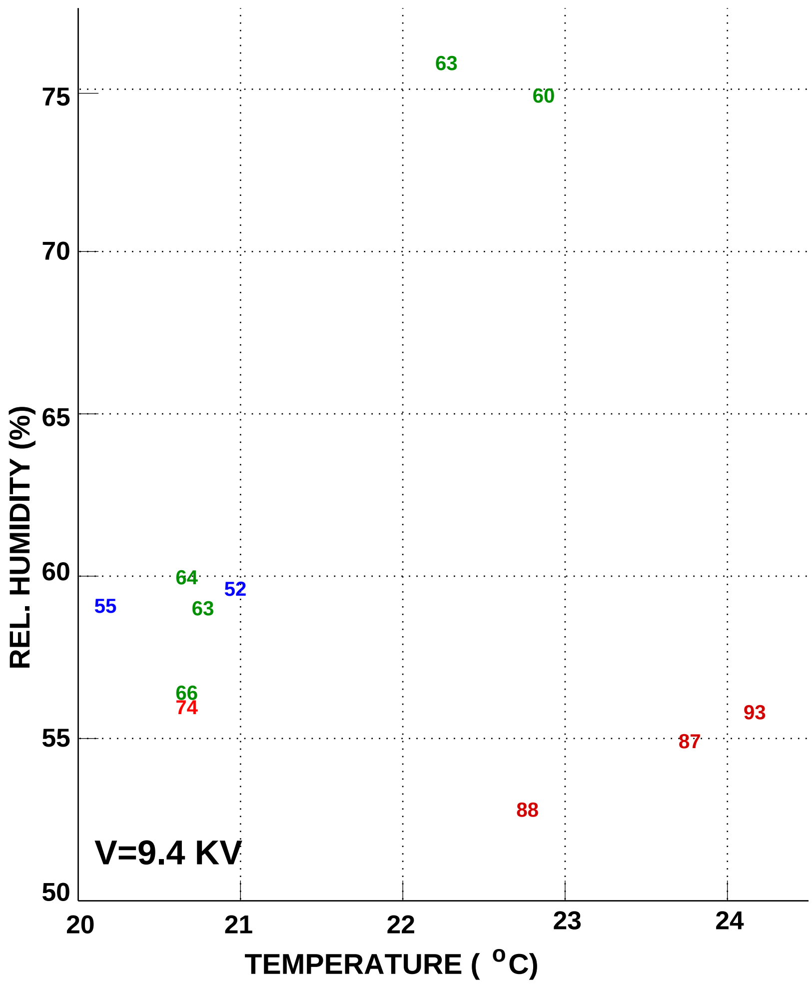

Figure 7: Efficiency of JB01 as a function of temperature (°C) and the relative humidity (%) for an applied high voltage of 9.4 KV. Typical errors on the efficiency values are 15%. The A/C was most stable at low humidity and it was difficult to get results at intermediate values.

It is seen that the efficiency values (ranging from blue–green-orange–red for efficiency values ranging from 50–60–70–80 and beyond, i.e., from low to high) increase with temperature and decrease with humidity. While 75% was the relative humidity in Mumbai at that time, it was not thought advisable to run the experiment for long at such high humidities, for fear of losing the RPCs. They seem to be fine so far; however, let's keep our fingers! Furthermore, at very high temperatures, the pulses were large and erratic, so that it was difficult to take data beyond about 9.5 KV. For instance, a lot of "sparking" was observed at 9.7 KV, as evidenced by sudden, large changes in the dark current which began to approach 0.7 μA.

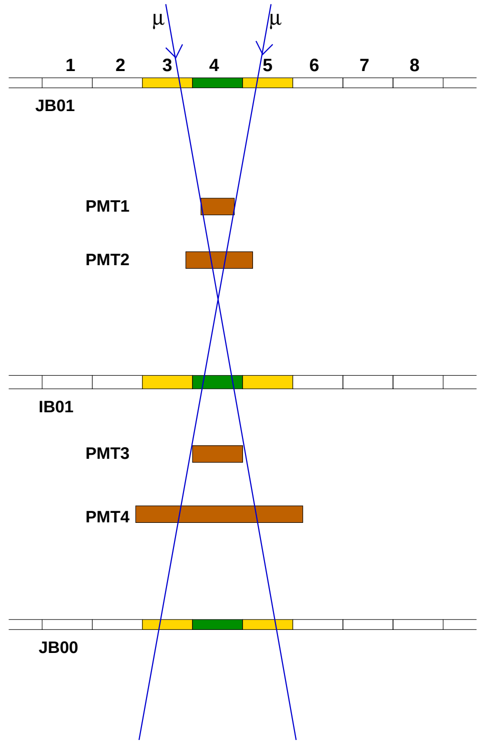

Figure 8: A "front" view of the geometrical set-up.

The results are consistent with the earlier result of 73% (with roughly 15% errors) which was at typical values of $T \sim 20°$C and $R_H = 55\%$. Unfortunately, the temperatures were not noted for the earlier runs although they are somewhere on the computer in the lab that was continuously monitoring this data before it was shut down for grounding repairs.

Similar trends were seen at different voltages (8.9 and 9.5 KV) and for JB00 as well, alhough there is less data here.

4.4 Cross-talk with JB01

Finally, we spent two days trying to understand the extent of cross-talk in the system. We focussed here mainly on JB01 although we have a few results for IB01 as well. To clarify, cross-talk is a loose word for the following:

1. The scintillators which provide the trigger are not correctly aligned and may allow for coincidence with the adjacent channel of the RPC to the central one (that is, channel 4).

2. The charged particle comes in at an angle to the vertical and just happens to trigger both the central and the adjacent strips. As can be seen from Fig.8, this can (should!) happen only for JB01 and JB00 when the alignment is otherwise correct.

3. When a muon goes through the RPC, the charge spreads and is insufficiently contained so that the adjacent strip alson picks up the signal.

Signal types (2) and (3) are symmetric phenomena, in that either neighbour has an equal chance of showing a coincidence with the central strip. In the second case, the probability of *all* three (central, that is, strip 4 and the two neighbours 3 and 5) showing a signal should be small. This can be seen from Fig. 8 where the maximal slant position of the incoming muon that can still trigger a 4-fold coincidence in the PMTs is shown by the tracks symmetrically on either side of the vertical.

The figure shows a “front” view of the set-up, showing the central 8 strips of the RPCs. The strip width (3 cm) of the RPCs is just commensurate with the narrowest paddles (of 2 and 3 cm for PMT1 and PMT3 respectively) that determine the allowed aperture for muons (4-fold coincidence in the circuit). The paddles are aligned with strip 4, also called the central strip. The neighbouring strips are distinguished by a different colour. Muons at a slant to the vertical that can still generate a trigger are shown by the symmetrical slant lines and can trigger the adjacent strips when the track passes through the neighbouring strips (3 or 5) marked in yellow for both JB01 and JB00. Since IB01 is centrally located in the geometry, provided the alignment is correct, there should be no incidences of type-2 signal.

In case 3, since the charge spreads, there is a significant probability of finding simultaneous pick-up in the central and two neighbouring strips. This is genuine cross-talk in the conventional sense. That is, whatever is measured for IB01 is genuine cross-talk, provided the alignment is correct.

Notes : Case 1 can be distinguished since here the probability of simultaneous signals in strips 4 and 5 is not the same as that for strips 4 and 3. But we are quite sure that our alignment is ok, which is no mean feat since there is very little space between the RPCs to maneauvre. Cases 2 and 3 can be distinguished by measuring the simultaneous firing of 3, 4, and 5, but due to lack of suficient electronics, we did not study these separately. We simply monitored the following cases:

- **A** : strip 4 fires when there is activity in *neither* 3 or 5: $4 \cap \left(\overline{3 \cup 5}\right)$.

- **B** : strip 4 fires when there is activity in *either* 3 or 5: $4 \cap (3 \cup 5)$.

The electronics for the cross-talk measurements :

As mentioned before, we were very short of electronics (especially logic units and amplifiers), so this limited our ability to make more measurements. JB01 and IB01 were the two RPCs with patch panel (for proper impedance matching as well as with external amplification possible) while JB00 had proper impedance matching but on-site pre-amplifiers that were not working properly. Also, IB01 was typically giving low efficiency due to unknown reasons (it’s also the one with 3 mm glass plates). So the available electronics was primarily used to study JB01. Three adjacent strips were monitored: strips 4 (central), 3 and 5 (neighbours). The logic checked for a signal in strip 4 always, and a signal in either 3 or 5 (never individually) whenever triggered by the 4-fold coincidence from the paddles; see Fig. 9 for details. For the case of IB01, only strips 4 and 3 were wired and the circuit always checked for a signal in either strip 4 or 3 when triggered.

Also, during this re-wiring, some stuff was fixed: all RPCs were moved to the same CAEN power supply; a patch panel was put on IB01, the hex amplifier was opened and an additional input connection that had been added at the back-end was removed so that the front-end (which is what was used) saw the proper impedance and the gain was reset to 50 for all channels.

The results are shown in Fig. 10 for both JB01 and IB01. In the case of IB01, there is no direct measurement of cross-talk since what was measured is the efficiency of triggering either strip 3 or strip 4. Since the earlier measurement only measured the efficiency of strip 4 (inclusive), a comparison of the two measurements as shown in Fig. 10 will indicate the extent of cross-talk. There is no perceptible cross-talk seen, but it must be remembered that the earlier measurements were made manually and these are made electronically. A data set measuring the (inclusive) efficiency of strip 4 with the same thresholds and using the same circuit is required before decisive conclusions can be reached; unfortunately, the lab had to be shut down for electrical repairs and I had to go home! In any case, it should also be remembered that in this configuration, whatever is observed in IB01 is *entirely* due to genuine cross-talk as the muons cannot pass through adjacent strips and still trigger a signal, as discussed earlier and illustrated in Fig. 8.

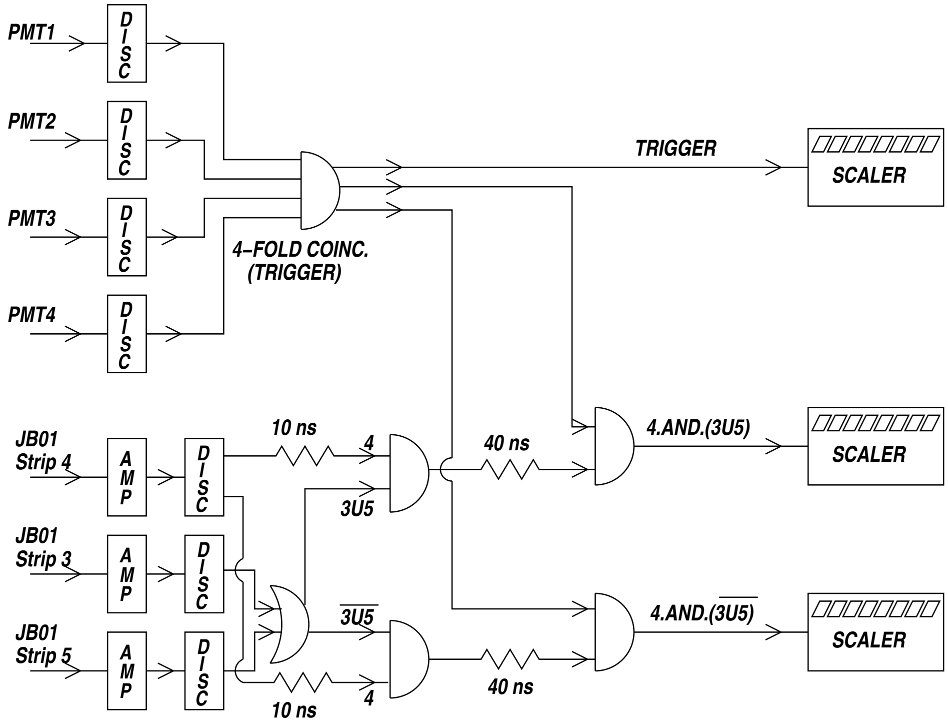

Figure 9: Circuit diagram to measure cross-talk in adjacent strips in RPC JB01. The trigger was provided by the4-fold coincidence of 4 scintillator paddles mounted on PMTs. Suitable delays were introduced in the circuit and scalers were used to count (a) the number of triggers, (b) the number of signals in the central strip 4 when either of the neighbours (3, 5) also fired, and (c) the number of signals in strip 4 when neither neighbour fired, over a fixed period of time, typically an hour.

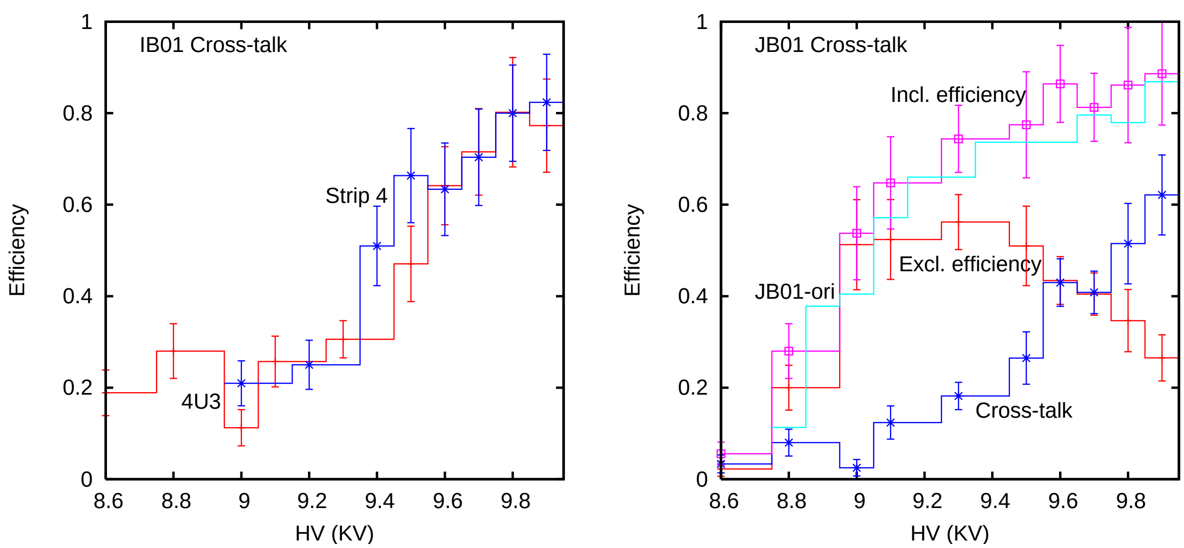

Figure 10: Left: Efficiency of signal pick-up in strips 4 or 3 ($4 \cup 3$) in IB01 as a function of the applied high voltage. Shown in comparison is the original measurement made (manually) for strip 4 alone. Right: Efficiency of signal pick-up in strip 4 alone ($4 \cap (\overline{3 \cup 5})$) and the extent of cross-talk ($4 \cap (3 \cup 5)$) in JB01 as a function of the applied high voltage. The sum of the two gives the total inclusive efficiency of strip 4, which is consistent with earlier measurements as shown in the figure.

For JB01, the three curves shown correspond to signals when only strip 4 was triggered (exclusive efficiency), when both strip 4 and a neighbour (3 or 5) were triggered (inclusive efficiency of strip 4), and finally, the extent of cross-talk. These can be defined as

$$\begin{aligned}\text{Excl. efficiency} &= \frac{4 \cap \left(\overline{3 \cup 5}\right)}{\text{trigger}}\,, \\ \text{Cross-talk} &= \frac{4 \cap (3 \cup 5)}{\text{trigger}}\,, \\ \text{Incl. efficiency} &= \frac{4 \cap \left(\overline{3 \cup 5}\right) + 4 \cap (3 \cup 5)}{\text{trigger}}\,, \end{aligned} \tag{1}$$

where the trigger is the 4-fold coincidence signal from the PMTs. It is seen that the extent of cross-talk increases with the applied high voltage, while the inclusive efficiency (that strip 4 fires at all) is consistent with earlier measurements (as seen in Fig. 6). There is a peculiar feature of the pulses especially at higher voltages when the avalanche is followed by a streamer: the pulse from strip 4 is usually the earliest, followed by the pulse from the neighbour. There are then two points where the pulse from strip 2 crosses the threshold, as can be seen in Fig. 11. At point A, strip 4 has fired (green pulse) but not the neighbour (yellow). At point B, both have fired. Hence, if both region A and region B are inside the coincidence window of the trigger, both the logic circuits $4 \cap (\overline{3 \cup 5})$ and $4 \cap (3 \cup 5)$ are true! It was seen from the oscilloscope that the gap between A and B was mostly greater than 20 ns.

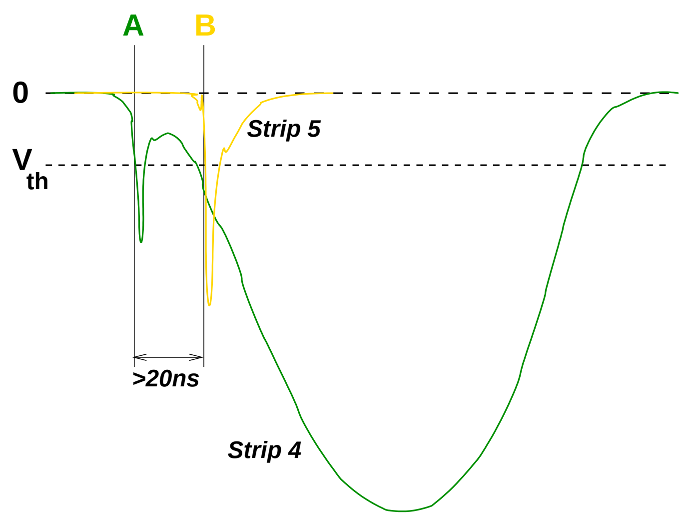

Figure 11: Pulse shape and timing from strip 4 and neighbour 3 or 5. Region A sets the logic circuit $4 \cap (\overline{3 \cup 5})$ to true while region B sets $4 \cap (3 \cup 5)$ to true. This can be avoided by pushing the region B out of the coincidence window of the trigger pulse.

This was taken care of in the earlier analysis by counting the coincidence of these two logic units and suitably subtracting. An attempt was made to reduce the coincidence pulse from the trigger to a width of 30 ns. In this case, most of the time the B-signal was outside the coincidence window and so the number of double-signals per event was greatly reduced. For example, at an applied high voltage of 9.6 KV, the rate of triggering of strip 4 alone (no cross-talk) went up to 60% from 43% and the cross-talk came down to 34% from 43%, that is, beyond 1σ, while the overall (inclusive) efficiency stayed around the same within 1σ errors: 95% to 86% earlier. However, now the question is whether cross-talk is defined as adjacent strips firing at all, or adjacent strips firing *within the time window*. I am not sure. Also, if the trigger is self generated, or by some number of RPCs themselves, without any scintillator paddle, as will be the case with the real ICAL, then

I am not sure how to remove these neighbouring signals. For sure they are there: either avalanche only or with a streamer as well, especially at higher applied voltages. This needs to be studied and understood better.

5 Brief description of work at BARC

Prof. Abe had said that cleaning was the essence of an RPC and so some small (30×30 cm^2) RPCs had been made after meticulous cleaning, as mentioned earlier. One of these RPCs was sent to BARC to the beautiful clean room in Prof Pant's lab. A streamer gas mixture of <8% isobutane, and roughly equal parts of freon and argon were flowed through the chamber for more than 24 hours, but pulses were still not seen. Also, beyond about 5 KV, the dark current was steeply rising and it was not clear why (only positive voltage was applied not equal and opposite voltages on each side of the glass, as was done in TIFR: it is not clear whether this matters).

After struggling with various possibilities the whole day, such as soldering on a high (10 MΩ) resistance in the high voltage circuit to see whether the dark current being displayed by the fancy dabba that provides the DC high voltage was indeed flowing through the circuit (it was), it was found that the reason there were no pulses was that one end of the patch panel was not actually soldered to the other end!!!!! After this was fixed, reasonable pulses were seen at 4.5–5 KV, but no more data was recorded as we were all exhausted. Note that the pulses were very clean and hardly any noise or ringing (both favourite occurrences in C-217 at TIFR) was visible on the oscilliscope. I hope that more work will be done on these RPCs soon and also that they won't die an untimely death because of being run in the streamer mode.

A relevant comment by Satyanarayana is that we should have used the Modi rather than the Japanese glass since that was the one that died soonest. If this RPC had been made with Modi glass and survived a month, that would have attested to the efficacy of the cleaning process. We would have to wait much longer to see the effect on Japanese glass. Unfortunately, we didn't think of this when making the RPC (any way, uncoated Modi glass was not available), but it will be nice if someone does make some Modi-glass RPCs and send it to BARC for testing.

Well, that's it. This is the sum total of work, with a lot of details to be filled in by Anirban and Devdatta. All I want to add now is a list of things to do and some impressions.

6 Discussion and further work

These are comments in no particular order or importance.

1. **Cosmic ray rate**: We are seeing roughly 140 to 150 counts per hour in the 4-fold coincidence circuit. In between we had a day when there was a huge increase in counts, both in all the RPCs and in the scintillators. We thought it could be a solar flare (one was reported) and after all, C-217 is on the top floor, but the data in the D-423 lab did not record any such increase. However, one piece of work that will be easy to do is to simulate the cosmic ray muon rate over the detector geometry as has been shown in Fig. 4 or Fig. 8 and verify the rates. This will be a nice simple monte carlo exercise.

2. **Threshold and noise**: It is possible to drastically decrease the RPC efficiency by setting too high a threshold, or to increase it conversely by setting the threshold of the discriminator so low that it triggers on noise. Since the system was very noisy (with constantly changing noise levels) we had to keep adjusting the thresholds which is a bad thing. If the noise was due to pick-up because of bad grounding, and this problem is now fixed in C-217, it is important to take another set of measurements aimed not so much as measuring the efficiency but to learn to fix the threshold once and for all.

3. **Temperature and humidity**: We do not have convincing data for temperature and humidity dependence but we have interesting pointers to a case for increasing the temperature. If we can increase the temperature, accepting higher dark currents, but decrease the operating high voltage, while retaining high efficiencies, that may be a gain worth studying.

4. **More on cross-talk**: This clearly needs to be understood better.

5. **More electronics**: I hope the BARC pre-amplifiers are now fixed and that more studies can be done. It is time to go beyond single-strip efficiency to a study of space and time localisation. For instance, we have only x-strips wired. We should also have y-strip information. Also, coincidence circuitry for both x- and y-strips as well as the logic for multiplexing the output of every 8th strip, etc., need to be tested before sending to the prototype.

6. **Self-trigger**: At some point, when we have enough electronics, we should retire the scintillators and self trigger with the RPCs. I am not sure how a trigger is generated using a set of say 4 or 5 RPCs. For example, if they are adjacent, then the timing will be few ns, not 60 or even 30 ns as we have been using for the coincidence window. Also, we cannot keep adjusting the delays: the trigger must keep the window open until the last RPC in the path of the muon has fired. Probably every experimentalist knows how to do this: it appears to be a mind-boggling problem since it seems to demand an advance knowledge of the track length! No doubt someone will educate me.

7. **Gas mixture**: Datar was suggesting SF_6. Maybe we should try for cheaper gases. Also, I haven't quite figured out how much gas flow is good, and whether that makes a difference (the gas quality inside the chamber depends on what fraction of it is being replaced). I don't know whether anyone has studied it but Prof. Abe was suggesting that we need to have very small replacing fractions.

8. **Complexity**: Until industry has been located to make the RPC chambers, it appears to me that making an RPC needs a lot of local expertise: glass cutting, painting, jigs, resitivity measurement squares, fancy types of sticking tape (conducting, insulating, good-looking, ...). An average lab may not have such specialised equipment (not that I am qualified to comment on what an average lab has, since the only two labs I have seen are the ones at TIFR and BARC).

   The electronics on the other hand (apart from the fast pre-amplifiers which anyway are not working!) seems to be fairly standard. If, as I heard in Delhi, many labs want to start working on RPCs, it may not be a good idea for people with limited resources to start making RPCs. It may be better (at least as a quick start-up format) for them to beg or borrow an RPC and get their gas system and electronics together.

   Also, note that once you have a gas system in place, there is a lot of routine built around it. You have to make sure security knows about it, that no-one smokes near the vent, that you never run out of gas, so you monitor it all the time (otherwise you will lose your RPC), etc. The gas system is one thing that needs every-day attention so if you want an RPC lab, you have to make sure someone visits it regularly (I guess you can take week-ends off once you are familiar with it)! Even if you switch off the RPC, the gas is flowing so it's there, a factor, all the time. But once you have a lab in place, it's fun. At least, I enjoyed it immensely. And once again, thanks to all who made it possible.