CERN-PPE-94-200

✓ CERN PPE/94-200 ✓
CERN/LAA-MC 94-33
October 11, 1994

SC 9451

**THE WIDE GAP
RESISTIVE PLATE CHAMBER**

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Abstract

The Resistive Plate Chamber (RPC) has good time and position resolution; these factors (coupled to its simple construction) make it an attractive candidate for muon trigger systems at future colliders. However, operated in spark mode, the RPC has severe rate problems that make it unusable above 10 Hz/cm². We have previously published our results concerning the operation of the RPC in spark and in avalanche mode; we have shown that the rate limit can be increased to 150 Hz/cm² if the RPC is operated in avalanche mode. Here, we discuss the performance of chambers with 6 and 8 mm gas gaps (compared to the more usual 2 mm gap). We outline the reasons for this choice, and also discuss anode versus cathode strip readout. We have measured the efficiency versus flux, and also show that an enhanced rate limit can be obtained if only a small region of the chamber is exposed to the beam (spot illumination). Finally we have tested the performance of chambers constructed with other materials for the resistive plate and compare it to chamber constructed with our preferred plastic, melamine laminate.

1. INTRODUCTION

The Resistive Plate Chamber is one of the simplest gaseous detectors to construct. Essentially it is two parallel plates enclosing a gas volume. The two plates are made of resistive material; electrodes are mounted on the outer surfaces of these plates. By applying voltage to these electrodes, an electric field is generated across the gas gap. If this field is sufficiently strong, electrons liberated in the gas by through-going ionising particles will avalanche and thus produce a signal on the external electrodes. The generated charge is deposited on a small region of the plate by the avalanche; this spot is slowly recharged by current flowing through the plate. If the electric field is even more intense, a 'spark' breakdown can be initiated by the avalanche. The resistive plates limit the discharge; in general there is a factor 10 to 20 increase in the charge generated by a spark breakdown compared to the avalanche signal. Initially RPCs have been operated in spark mode; the large pulse makes front end amplifiers unnecessary - however spark mode operation has many problems. These problems are the rate limit, the time walk with rate, after pulsing and the use of a flammable, 'non-green' gas. These problems are reduced if one operates in avalanche mode. In our previous publications [1,2] we have discussed the avalanche mode of operation.

Here we are going to report on RPCs with 6 and 8 mm gas gaps operated in avalanche mode. Our standard chamber has plates made from melamine-phenolic-melamine laminate (also known commercially as Formica); these plates are 1.2 mm thick. Previously [1] we have found that the rate cut-off for melamine laminate is 10 times higher than for phenolic plates. We have tested two other plastics, PVC with ionic doping [3] and ABS plastic [4] and also Schott glass type 8540. We will discuss the results below. Most tests took place in the CERN East Hall test beam, T9, using a defocused beam covering the whole active surface of the chamber (unless stated otherwise).

2. THE REASON FOR THE WIDE GAP

As previously stated the avalanche process can lead to a spark breakdown. If one chooses to work in avalanche mode one needs to use a sensitive amplifier. The occurrence of sparks has to be minimised to avoid firing neighbouring amplifiers; this would lead to large cluster sizes.

The gas gap in an RPC is used both for gas gain via the avalanche process and also as the source of primary ionisation. The avalanche pulse is generated by a multiplicative gas gain across the gas gap, thus the largest gain is from electrons that traverse the whole gap. An electron that is produced at a distance x from the anode will have a gain of $G^{(x/D)}$, where D is the distance between the anode and cathode plate, and G is the gain of an electron traversing

the whole gap. A minimum ionising particle traversing a gas volume containing Argon (a typical gas used in gaseous detectors) produces 30 primary ionisation clusters per cm (thus 3 clusters/mm on average). Using Poisson statistics one finds a 5% probability that there are no clusters of primary ionisation in the first millimetre of the gas gap. We wish to work close to 100% efficiency; this implies that the gain for a single electron over the remaining gap has to be large enough to produce a pulse that can be discriminated by our electronics (e.g. 10^5 electrons). Thus for this limiting case (no clusters in the first millimetre) there remains only 1 mm of the 2 mm gas gap to produce an avalanche signal above our discrimination level. If we set the avalanche gain to be 10^5 across this 1 mm, then one has a gain of 10^{10} for an electron that avalanches over the full 2 mm. However, for a chamber with an 8 mm gas gap, there remains 7 mm for the avalanche process; thus, in this case, one sets the gain to be 10^5 over 7 mm, which gives a gain of $5.2 \cdot 10^5$ for an electron that traverses the full 8 mm. Thus there is a dramatic reduction of dynamic range of avalanche pulse size (10^5 is reduced to 5.2) with a larger gas gap (2 mm increased to 8 mm). As sparks are usually associated with a high density of positive ions (10^8 is the threshold for the production of sparks in parallel plate chambers with metallic plates), it would be no surprise if a larger gas gap reduces the probability of sparks. We have performed a measurement [2] to check this and have found a 30% probability of a spark for a 2 mm gas gap working at maximum avalanche efficiency of 95%. This spark probability drops to zero for an 8 mm gap. Additionally, using the above reasoning, it is difficult to work at efficiencies above 95% with a 2 mm gap (if normal types of gas mixtures are in use). However with a larger gap one can be sensitive to avalanches from electrons originating further than 1 mm from the cathode. Thus chambers with larger gas gaps will have higher detection efficiency. Results that support this can be found in ref. [2].

Another aspect of avalanche mode operation is that the gas gain varies strongly with the electric field and thus with the physical size of the gas gap. We have used the measurements of the Townsend coefficient by Sharma and Sauli [5]. We have considered a 2 mm and 6 mm gas gap with various mixtures of Argon and isobutane. We have chosen to vary the gap dimension by ± 100 micron; this would seem a reasonably obtainable value for the mass production of thousands of square metres of RPC. For a gas gap of 2 mm with the gain set to $10^4/\text{mm}$ we find a variation in gain from $\sim 7 \cdot 10^2/\text{mm}$ to $\sim 5 \cdot 10^5/\text{mm}$ (a gain ratio of ~ 700) as the gap width varies from 2.1 to 1.9 mm. However varying the 6 mm gas gap, the gain changes from $\sim 3 \cdot 10^3/5 \text{ mm}$ to $\sim 4 \cdot 10^4/5 \text{ mm}$ (a gain ratio of ~ 13). If one works at higher gains, setting the single electron gain to be 10^5 , the 2 mm gap has a gain variation from $\sim 4 \cdot 10^4/\text{mm}$ to $\sim 1 \cdot 10^7/\text{mm}$ (a gain ratio of 250) for the ± 100 micron gap variation. For the 6 mm gas gap, the corresponding gain variation is from $\sim 2 \cdot 10^4/5 \text{ mm}$ to $\sim 6 \cdot 10^5/5 \text{ mm}$ (a gain ratio of 30). The exact variation depends on the gas mixture, and of course it is possible that careful selection of the gas could reduce this effect. However, there are also other constraints

(such as gas flammability). From this we learn the following: a chamber with a 2 mm gas gap and built with reasonable mechanical tolerances can not be operated with a gas gain of $10^4/\text{mm}$, if high efficiency is the goal (since increasing the gap to 2.1 mm reduces the gain to ~ 700 , which is too low a gain to produce a reasonable signal). Thus we will have to work with gas gains in the order of $10^5/\text{mm}$. Therefore the 2 mm gas gap will have yet another factor of ~ 200 in dynamic range on top of the 10^5 produced by the distribution of primary ionisation. However RPCs with wider gaps (6 mm in this example) can tolerate a gap variation of ± 100 micron.

For these reasons we have decided to work with 6 mm and 8 mm gas gap. However an alternative approach would be to use a heavy gas, which has an increased density of primary ionisation clusters for through-going minimum ionising particles. We intend to test such gases as C_4F_{10} , where the number of primary ionisation clusters could be in excess of 150 clusters/cm. One could also consider working at lower gains but since the RPC is envisioned to be used for large area coverage (with long pick up strips), a pulse size of 10^5 electrons may already be at the limit.

3. STRIP READOUT

The cross section of a typical test chamber is shown in figure 1. The two outer plates of Lucite are for mechanical support. Either a positive or negative voltage can be applied to the high voltage electrode, and thus the readout strips (held at zero volts by the electronics) can effectively be either cathode or anode readout strips. The strips are 12.5 mm wide on a 15 mm pitch. Using the electronics shown in figure 2 we have measured the efficiency and number of strips that fire. We find a big difference between anode and cathode strip readout. For cathode strip readout generally 2 strips fire per particle, while for anode readout only one fires. This is shown in figure 3. We also show the efficiency versus threshold in figure 4; the efficiency is slightly higher for the anode readout. These results are not unexpected. The maximum gain of the avalanche process is close to the anode plane. The anode strips are located on the other side of the 1.2 mm thick RPC plate, thus one expects that most of the signal will be on one strip. However the cathode strips are located at a 9.2 mm distance; thus the signal is shared between strips. However it seems almost too good, only 10% of events fire two strips for the anode readout. We have looked at the signals on the strips (with cosmic rays) for both cathode and anode readout. For cathode readout one finds, as expected, that a positive-going signal is shared between strips. For anode readout, one finds a negative-going signal on the strip closest to the avalanche, but often one finds that the neighbouring strip has a positive going signal. We show the waveforms observed on cathode and anode strips for two typical events in figure 5. The positive going pulse on the nearest neighbour is due to the effect of induction [6] and 'turns off' the neighbouring strips; thus the strip multiplicity is reduced.

We have modified the electronics for one chamber to make use of this positive going pulse - and also to add common mode rejection so that the electronics is less liable to oscillate. The layout is shown in figure 6. We found that the number of clusters of two hits was reduced from 10% to 5% . However the positive going signal on the neighbouring anode strips ($i-1$ and $i+1$) causes the strips $i-2$ and $i+2$ to fire in some cases; and thus 3 (unclustered) strips to fire; these events were eliminated from the analysis. Obviously this is not a satisfactory solution and the electronics needs further development. However we used this electronics to test whether the angle of incidence of the particle altered the ratio of single strip to double strip fired. The majority of the avalanche signal is generated by electrons that avalanche over the full gas gap (i.e. electrons that originate close to the cathode). Thus it is not unexpected that the angle dependence should be small (even with the 8 mm gas gap). The result confirming this expectation is shown in figure 7.

One probable use of RPCs is to provide a muon trigger for future collider experiments. It will be necessary to identify a track segment that points back to the interaction point. The chambers will be arranged so that a roadway of hits in the various chambers define such a segment. If more than one strip fires then a wider region has to be searched for possible hits, and the on-line P_T cut is less sharp. Figure 7 indicates that anode strip readout of RPCs is ideally suited for muon trigger implementation and this readout works well even at large angles of incidence.

4. RESISTIVITY MEASUREMENTS

We have measured the resistivity of various materials. For a particular resistive plate under test, we cover an area on both surfaces with conductive paint. We mount this within a gas tight box through which we flow bottled nitrogen (presumably dry, although no extra precautions were taken to remove small traces of water vapour). A voltage is applied, usually 1000 volts, and the current measured. Figure 8 shows the variation of the resistivity of four plastics over a 3 month period. These plastics have been used by us and others for RPC construction. In all cases the resistivity increases; only the doped PVC showed a relatively quick stabilisation. However even for this plastic the resistivity increases by 2 orders of magnitude. The resistivity reduces again if the plate is exposed to humid air, and in fact we can control the resistivity by changing the percentage of water vapour in the nitrogen gas. With 1% water vapour a melamine-phenolic-melamine plate has a resistivity of $2 \cdot 10^{12} \Omega \text{ cm}$.

Before we added water vapour to the gas mixtures we found that the working voltage of the chamber could change by as much as 1000 volts (in 12,000) over several months. We believe that this change in working voltage is due to the change in resistivity. There is a small leakage current through the plates, and thus there is a voltage drop across the plate. This

voltage drop is dependant on the resistivity and thus affects the electric field across the gas gap. We found no dependence of the rate cut-off with this change in resistivity.

To reduce this change of resistivity, we add 1% water vapour to all our gas mixtures. We do this by bubbling half the gas through a water bubbler, nominally at room temperature of 20° C. We will temperature control the water bubbler for future tests. We show, in figure 9, the working voltage of a chamber (5 mm gas gap) over a 3 month period. In order to define an accurate value of the working voltage, we took the voltage for which the efficiency was 80% (on the rising edge of the efficiency plateau). The working voltage follows the changes in atmospheric pressure well, however there is a 100 volt (in 15 kV) decrease over the full time interval of the measurement. This could be caused by many effects including a systematic shift in gas composition and water content. A change in the exact voltage put out by the high voltage power supply can not be excluded. The addition of water vapour controls the resistivity but more careful and systematic tests have to be performed to understand long term stability.

5. RATE MEASUREMENTS

In our first studies [7] of the RPC (working in spark mode) we found that one could measure an enhanced rate capability if only a small region of the chamber was exposed to the beam (spot illumination) compared to the rate limit measured when the whole active area was exposed to a uniform flux (flood illumination). For a 'standard' RPC (phenolic plates 2 mm thick, 2 mm gas gap operated in spark mode) we found a rate limit (the rate where one has a 10% drop in efficiency) of 1 Hz/cm² with flood illumination. This should be compared to the 100 Hz/cm² rate limit measured by Bertino et al.[8]. The measurement of Bertino et al. was performed by exposing a 3 cm diameter region of a 2 x 1 m² chamber to a test beam (i.e. spot illumination). Previous to our test Iori and Massa [9] found a similar low rate cut-off by exposing the same 2 x 1 m² chamber to a flux of photons at a nuclear reactor (i.e. flood illumination). Thus in subsequent tests we always make our rate measurements with a defocused beam and small chambers (25 x 25 cm²), so that the whole active area is exposed to the beam. The spill time of the PS in the East Hall is 0.4 seconds. When working in spark mode we would find a big change in efficiency during the spill, however with avalanche mode operation we find that the change in efficiency happens during the first 20 ms of the spill. We thus quote the efficiency by integrating over the whole spill.

Despite this observed difference between the rate limits obtained with spot or flood illumination, other groups continue to publish the rate cut-off obtained with spot illumination. Recently Bencze et al.[10] state that they do not observe a difference in the rate limit obtained when they expose a 2 x 2 cm² region of their 50 x 50 cm² chamber to a beam (spot illumination) compared to the rate limit measured when the whole active area is illuminated

with a source [11]. We had only measured the rate limit difference between spot and flood illumination for RPCs operated in spark mode. Thus, a possible explanation for Bencze et al. observation, is that one obtains similar rate limits for spot and flood illumination if one works in avalanche mode. To check this, we have tested our chamber (operated in avalanche mode) with spot illumination (beam spot of 10 cm^2 with a chamber area of $25 \times 25 \text{ cm}^2$) and compared the rate cut-off to the case where the beam is defocused and the whole active area is illuminated. We show the result in figure 10. We find a large difference between spot and flood illumination. The rate for the focused beam is calculated by assuming that the beam spot is uniform over 10 cm^2 . In reality this underestimates the flux; the flux in the centre of the beam spot is probably one order of magnitude higher than shown. Since the rate limit is 10 times higher for spot compared to flood illumination - this implies that the area of the RPC affected by the 10 cm^2 beam spot is $\sim 100 \text{ cm}^2$ i.e. a spot of radius 6 cm.

This test, described above, shows that if the RPC is used in a situation where there is a local hot spot, this hot spot can have a relatively high rate without affecting the capabilities of the chamber. However, if the flux is uniform over a large area then one should be cautious using rate limit obtained with spot illumination. We do not understand why Bencze et al. [10] observe no difference between spot and flood illumination. The RPC that they test is different in construction. It has phenolic resistive plates coated with linseed oil and a 2 mm gas gap. The gas used contains freon; thus a different mode of operation is possible.

We have built chambers with three other materials for plate material; ionic doped PVC (1 mm thick)[3], ABS plastic (0.5 mm thick)[4] and Schott glass type 8540. The two plastics are less rigid than melamine laminate and have to be glued to the Lucite plate to ensure flatness. The PVC, although it had a shiny finish, had many small points and blemishes in the surface. Another chamber was constructed using a thinner melamine-phenolic laminate (0.8 mm thick). All the chambers were constructed with an 8 mm gap. We show, in figure 11, the efficiency versus rate for these chambers together with measurement from our standard chamber constructed with melamine-phenolic-melamine laminate of 1.2 mm thickness.

We show two curves for the ABS plastic, the curve at lower efficiency was taken when the chamber was first constructed. During this measurement there was a high dark current drawn by the chamber ($\sim 30 \mu\text{A}$) at the peak of the efficiency plateau. Other RPCs (of $25 \times 25 \text{ cm}^2$ active area) usually draw less than $1 \mu\text{A}$ at peak efficiency. We left this chamber on the shelf for 6 months and retested it. During this second test the dark current was normal ($>1 \mu\text{A}$); also the efficiency was comparable to other chambers. We do not know whether this beneficial ageing was due to (a) some surface effect of the ABS plastic, or (b) due to the increase in resistivity as the plates dried out. Whatever the reason it is clear that the RPC works best if there is a very small dark current.

We observed a very high noise rate with the PVC chamber - probably due to the blemishes on the surface; it was also necessary to operate this chamber at 15 kV for maximum efficiency (compared to 14.5 kV for the melamine laminate chamber). It would be interesting if we could obtain this PVC without blemishes - as maybe the rate limitation is partially limited by the high level of noise.

The Schott glass chamber is promising; the rate cut off is similar to a melamine laminate chamber. However the plate thickness is 2 mm. In the past [2] we have found a big improvement in rate capability for thinner plates (for example, a melamine laminate RPC in spark mode gave a 30 fold improvement of the rate limit when the plate thickness was decreased from 3 mm to 1.2 mm). Thus one could expect a substantial improvement if thinner glass plates were available. The glass plates used in our test were sliced out of a larger block of glass and then polished; this is rather a costly approach. A cheaper mass production method needs to be found capable of producing glass sheets of at least 1 m² if this glass is to be seriously considered for RPC construction.

6. EFFICIENCY PLATEAU SHAPE

One of the outstanding problems concerned with the RPC is the shape of the efficiency plateau. We measure the efficiency as a function of applied high voltage; the efficiency increases until it reaches a maximum value (close to 100%) and then starts to decrease with increasing high voltage. A similar observation was made for RPCs operated in spark mode. However, in spark mode, the addition of freon to the gas mixture solves this problem. A small addition of freon (2% to 8%) produces a flat plateau at high efficiency. Unfortunately we do not observe a similar improvement on addition of freon when the RPC is operated in avalanche mode. We show in figure 12 the plateau curves of our RPC for various mixtures of argon and isobutane. It appears that a higher concentration of isobutane extends the flat top of the efficiency plateau.

We show, in figure 13, the efficiency plateau for 20% Isobutane 80% Argon for various fluxes. We see no change in working voltage for the different rates; in general the peak efficiency is shifted to a lower value, but the voltage remains the same. For this reason our efficiency versus rate measurements have been performed by first finding the voltage that gives the highest efficiency (usually at a flux of ~100 Hz/cm²) and then varying the flux. Bencze et al [10] report that the high voltage has to be increased from 6700 to 7900 volts to work at higher fluxes when they were working in their 'low gas gain' mode. We observed a similar voltage and flux correlation in our initial studies of RPCs operated in spark mode; however in avalanche mode (as shown in figure 13) this effect is no longer apparent.

7. TIMING

We have shown previously [2] that a 4 mm gap chamber operated in avalanche mode, has no time walk and a constant FWHM of 6 ns with various rates. These measurements were made with a constant fraction discriminator. For a wide gap chamber the formation time of the avalanche itself plays a role, especially as one is working at lower electric fields. Thus, the rise time of the pulse will become longer (the avalanche has to traverse 6 or 8 mm) and will depend on the drift velocity of the electrons in the gas. This drift velocity depends on the gas composition and the electric field. The avalanche is terminated by the electrons arriving at the anode. The movement of positive ions is slow and plays no role in the shape of the fast pulse. Thus the fall time of the avalanche signal will be affected by the fall time of the electronics and also the capacitance of the pickup strip. In figure 14 we show the timing of the leading and trailing edge using our simple threshold discriminator for two different gas mixtures. The chamber has a 6 mm gas gap. Gas mixture A (upper plots) is for 10% isobutane 90% Argon with an electric field of 15 kV/cm. Gas mixture B (lower plots) is composed of 15% isobutane, 15% CO₂ and 70% Argon with an electric field of 22 kV/cm. The time axis is in TDC counts, each TDC count is one nanosecond. One sees that the avalanche formation for gas mixture A is slower by 60 ns. This can be seen from both the increased width of the rising edge spectrum and from the change in the absolute time of the falling edge. The width of the falling edge spectra must in some degree depend on the drift time over the first millimetre (close to the cathode); this is broader for the slower gas (mixture A). The time spectra of the average (of the leading and trailing edges) is narrower than either individual spectra - as, in effect, one is performing a slewing correction. For gas mixture B the FWHM of 8 ns of the average is sufficient to be used to select the correct bunch crossing at LHC (25 ns between successive bunch crossings).

We have studied the time resolution further by applying a correction based on the measured pulse width to the leading and trailing edge time (i.e. a slewing correction). In figure 15 we show the resultant spectra; we also show the spectrum of the average of the leading and trailing time. The FWHM are all very similar, however there is a significantly larger tail for the leading edge spectrum. We believe that all these spectra can be further improved, as there was a 60 MHz oscillation in the preamps. This oscillation produces large structure in the width spectra.

One concludes from this that one needs a gas with a fast drift velocity for the best timing. It is also clear that more precise timing can be obtained from the trailing edge. It is possible that using preamplifiers with a faster fall time may allow good timing to be obtained without using slewing correction. This could also eliminate the expense and complexity of constant fraction discriminators. Other simple algorithms (such as the average) should also be considered for timing purposes.

8. DISCUSSION

We have discussed the performance of a wide gap RPC operated in avalanche mode. An important factor for avalanche mode operation must be the absence of spark breakdown. We have shown that the wide gap is the first step to achieving this; the resultant chamber has extremely attractive features: low strip multiplicity and reasonable rate capability. The timing resolution is sufficient for LHC use (with the particular gas mixture that we have tested here); however the short plateau length and drop in efficiency with increasing voltage need to be solved before construction of a large number of square metres. This fall in efficiency with increasing voltage is somewhat a mystery. However it is certainly dependant on the gas mixture. Thus we intend to start on a systematic evaluation of gas mixtures.

We have shown that melamine laminate still gives the best rate capability. The rate capability can be enhanced by reducing the plate thickness from 1.2 mm to 0.8 mm. It appears that 1 kHz/cm² with 95% detection efficiency is probably obtainable (with flood illumination), however higher rates are probably not possible with this plastic. As a similar rate capability can be obtained with 2 mm thick Schott glass (type 8540), a possible route to an RPC with a higher rate capability could be to use thinner glass.

We have differences with the results of Bencze et al.[10]. We observe a big difference in rate capabilities between spot and flood illumination, and also do not have a significant shift in working voltage with rate. Is it possible that they operate in a different mode to us? A quenched spark (streamer) mode suggests itself for the high freon concentration.

Acknowledgements

As usual we have enjoyed the excellent services of the PS test beams in the East Hall, and thank everyone involved that makes this possible. The two other plastics that we have compared to melamine laminate were supplied by Dr. N. Morgan from V.P.I. and Dr. Ables from L.L.N.L. The design of the pre-amplifier is based on the work of Alan Rudge. LeCroy Corporation came to our rescue with a temporary loan of a 2277 TDC. Many thanks for the friendly co-operation.

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FIGURE CAPTIONS

- Figure 1. Cross section of a typical RPC used in our tests. The Lucite plates are for mechanical support
- Figure 2. Circuit diagram of front end electronics.
- Figure 3. Distribution of number of strips per cluster for through going particles for anode and cathode strip readout
- Figure 4. Efficiency versus threshold for anode and cathode readout. The threshold is measured at the input of MVL407.
- Figure 5. Waveforms on two neighbouring strips for cathode and anode readout.
- Figure 6. Schematic of modified electronics.
- Figure 7. Efficiency and probability of single strip clusters versus angle of incidence.
- Figure 8. Resistivity of various plate materials over time, when left in a dry atmosphere.
- Figure 9. Operating voltage for a chamber and atmospheric pressure over a 3 month period.
- Figure 10. Efficiency versus rate for a focused and defocused beam.
- Figure 11. Efficiency versus rate for various chambers. The doped PVC chamber was tested with a gas mixture of 70% Argon, 9% isobutane, 13% CF₄·8% CO₂. The Schott glass was tested with 80% Argon, 13% CO₂ and 7% isobutane. The other chambers were tested with 80% Argon, 20% isobutane. The ABS plastic chamber was tested and gave the lower curve, six months later it was retested and gave the upper curve. See text for more details.
- Figure 12. Efficiency versus voltage for various Argon/Isobutane mixtures.
- Figure 13. Efficiency versus voltage for various particle rates.
- Figure 14. Time spectra for the leading edge, the trailing edge and the average (of the leading and trailing) for the avalanche pulse for two gas mixtures. The RPC had a 6 mm gas gap.
- Figure 15. Corrected time spectra: the correction was based on the measurement of the discriminated pulse width. The average is the average of the leading and trailing edge.

Figure 1

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