

Progresses in the simulation of Resistive Plate Chambers in avalanche mode

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New results about the simulation of Resistive Plate Chambers are reported; particular emphasis is put in the understanding of charge spectra in regions where deviations from the pure avalanche mode of operation can be present.

1. INTRODUCTION

The interpretation of the experimental charge spectra of Resistive Plate Chambers (RPCs) is an intriguing issue. Many qualitative arguments have been proposed to explain the experimental data; these data differ significantly from author to author, and a comprehensive explanation of the different results is quite difficult. On the other hand, a detailed simulation program of the avalanche multiplication processes in RPCs has already been developed and explains well many of the observed features of this detector [1].

Let us focus our attention on the case of 2 mm single gap RPCs, for which different studies have been reported. Experimental data have shown that the shape of the charge spectrum of this device changes with increasing voltage. When the operating voltage is sufficiently low, the spectrum is monotonically decreasing; when the operating voltage approaches the one corresponding to the knee of the efficiency plateau, or it is higher, the spectrum approaches a Landau, or even Gaussian, shape (see, for instance, [2] and [3]). The average value of the Gaussian peak, and even the average value of the spectrum, change significantly with the gas mixture.

On the other hand, the simulation predicts that the charge q_{ind} induced on pick-up electrodes should follow, more or less, an inverse power law distribution, of the type:

$$f(q_{ind}) = R q_{ind}^{\lambda-1} \quad (1)$$

where R is an appropriate normalization constant, η the first effective Townsend coefficient, and λ the primary ionisation density. Its shape should not change with increasing voltage. Therefore there are two main differences between the simulated and the observed spectra for 2 mm single gap RPC operated below the knee of the efficiency plateau; experimental charge distributions are characterised by:

1. a lack of events near the origin, which leads to full efficient detectors;
2. a broad peak of events, instead of long tail towards the right, as predicted by (1).

This paper is devoted to try to explain these differences; since the two outlined problems involve different types of phenomena, they will be examined separately. To clarify the former, in Sect. 2 some statistical calculations about the number of events giving rise to an induced charge below a certain threshold are briefly outlined. For

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the latter, in Sect. 3 possible space-charge effects on the charge distribution are treated.

2. THE CHARGE SPECTRUM NEAR THE ORIGIN

Let us focus now our attention to the charge distribution near the origin; this is closely related to the detector efficiency. The charge q_{ind} induced on an external pick-up electrode by one cluster developing exponentially into an avalanche is given by:

$$q_{ind} = \frac{q_e}{\eta g} \Delta V_w n_0 M \left[e^{\eta(g-x_0)} - 1 \right] \quad (2)$$

where q_e is the elementary electron charge, g is the gap width, ΔV_w is the weighting potential drop inside the gap, M is an avalanche fluctuation factor (with average 1), and x_0 is the initial position of the cluster, which contains, at the beginning, n_0 electrons [4]. For an event to be revealed, the condition $q_{ind} > q_{thr}$, where q_{thr} is the electronic threshold level, has to be fulfilled. Inverting this condition, one obtains:

$$x_0 < g - \frac{1}{\eta} \ln \left(\frac{q_{thr}}{A} + 1 \right) \quad (3)$$

where:

$$A = \frac{q_e \Delta V_w M n_0}{\eta g}$$

In the case of the cluster closest to the cathode, which gives rise to most of the induced charge, x_0 is distributed according to a decreasing exponential:

$$P(x_0) = \lambda e^{-\lambda x} \quad (4)$$

Therefore the probability that x_0 satisfies the condition (3), is given by the integral of (4) between 0 and $g - \frac{1}{\eta} \ln \left(\frac{q_{thr}}{A} + 1 \right)$. This is just the efficiency ϵ of the chamber:

$$\epsilon = 1 - e^{-\lambda \left[g - \frac{1}{\eta} \ln \left(\frac{q_{thr}}{A} + 1 \right) \right]} \quad (5)$$

The efficiency, as computed with expression (5), is reported in Fig. 1; here $\lambda = 5.5 \text{ mm}^{-1}$ and the average values for $n_0 = 3$ and $M = 1$

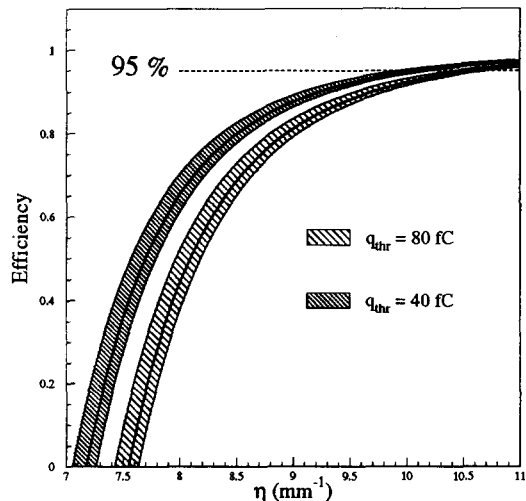


Figure 1. Efficiency versus η with different electronic thresholds.

have been used. The two full lines correspond to the choices of $q_{thr} = 80$ or 40 fC ; note that, since RPCs are generally read-out with strips, half of the charge is lost because of the termination at one end, and this means that the actual discrimination threshold of front-end electronics has to be a factor two lower.

The shadowed areas in Fig. 1 represent two possible refinements of expression (5). In fact, while this is correct for the first cluster, other expressions hold for the other clusters and a formula for the “total” efficiency (i.e. taking into account the contribution of all clusters) can be obtained. However, the first cluster is created at an average distance $1/\lambda$ from the cathode, the second at $2/\lambda$, and so on; this implies that each cluster induces, on the average, a charge a factor $e^{-\eta/\lambda}$ smaller with respect to the previous one. A 2 mm single gap RPC is typically operated at $\eta \sim 9 \text{ mm}^{-1}$; therefore the ratio $q_{ind}^{2nd}/q_{ind}^{1st} = 0.2$, $q_{ind}^{3rd}/q_{ind}^{1st} = 0.04$, and so on. A crude approximation can be done assuming that the total induced charge is a factor ~ 1.25 greater than the one resulting from (2) (practically the factor A has to be multiplied by 1.25). This is an overestimation, since the position probability distributions of the

clusters following the first vanish near the origin, and therefore events with charge larger than the average are non likely.

The second refinement descends from the fact that the probability distributions of n_0 and M are asymmetric with respect to their averages, having much more events toward the origin; this means that, assuming n_0 and M constant and equal to their averages leads, again, to an efficiency over-valuation.

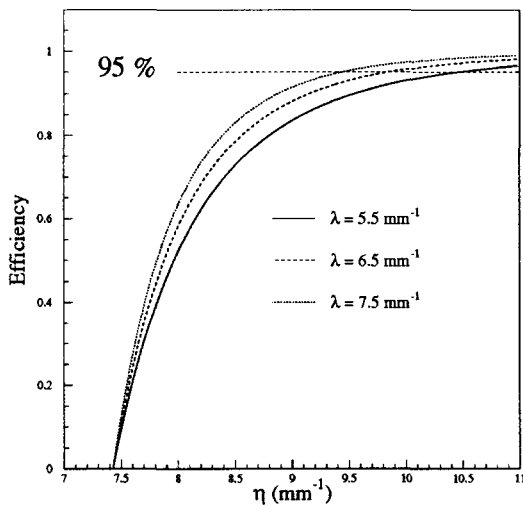


Figure 2. Efficiency versus η for different value of the primary ionisation coefficient.

Summarizing, there are two opposite effects: the former is the fact that many clusters are, in general, present in the gas gap, the latter is the asymmetry of the probability distributions. To take into account these two effects, in Fig. 1 the shadowed areas are delimited by two curves obtained by taking expression (5) with the factor A multiplied by 1.25 or by 0.85; the two pairs of curves might represent, therefore, a range of possible variation of the computed efficiency. In the four cases an efficiency greater than 95% is reached only when $\eta > 9.5 \text{ mm}^{-1}$; an efficiency close to 98 % is obtained with $\eta > 10.5 \text{ mm}^{-1}$.

These η values are much higher than the ones reported in literature; anyhow, at the operating voltages corresponding to these values, there would be a significant streamer contamination. Experimental data, on the other hand, show that single gap RPCs seem to be full efficient with a very low streamer fraction. The results reported here descend directly from simple statistical arguments, based essentially on the assumption of the Poisson distribution for the primary cluster position, and and exponential development of the avalanche. Since we are talking about small charge events, which not should be affected by space charge effects, deviations from the exponential law are unlikely.

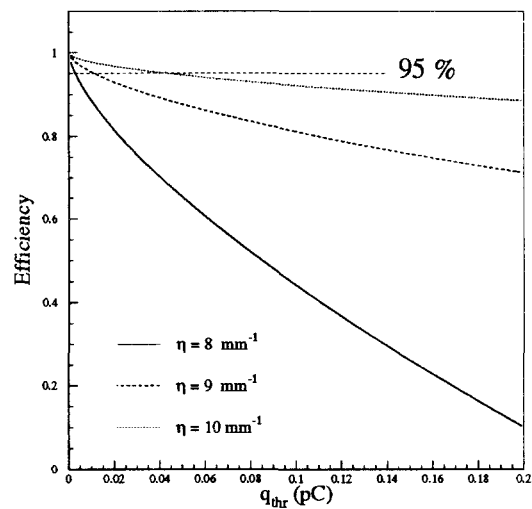


Figure 3. Efficiency versus q_{thr} for different η values.

Higher efficiency could be obtained using $\lambda > 5.5 \text{ mm}^{-1}$, the value used up to now. The efficiency computed taking $\lambda = 5.5, 6.5$ and 7.5 mm^{-1} , in the most favourable hypothesis of $A \rightarrow A \times 1.25$ is shown in Fig. 2 as a function of η . For $\lambda = 7.5 \text{ mm}^{-1}$ an efficiency $> 95\%$ is reached when $\eta > 9.2 \text{ mm}^{-1}$, $\epsilon > 98\%$ when $\eta > 9.7 \text{ mm}^{-1}$. However, at the light of the data reported in literature, such λ value seems unlikely.

Obviously, to obtain high efficiency, q_{thr} could be set conveniently low; the efficiency for three values of η is reported in Fig. 3, as a function of q_{thr} , (again in the case $A \rightarrow A \times 1.25$). For $\eta = 9 \text{ mm}^{-1}$, q_{thr} must be lower than 15 fC (which correspond to 7.5 fC of discriminator threshold, a value much lower than the noise usually measured in practical conditions).

Another possibility is that the position distribution of the primary clusters is not correct; this might be if these clusters occupy a certain amount of space and are not point-like. Finally, phenomena of electron extractions from the cathode, or photoionisation in the gas, could be present; this is the most probable hypothesis, which, however, cannot be proved experimentally.

3. THE RIGHT TAIL OF THE CHARGE SPECTRUM

Here the basic idea is that the avalanche development deviates from the simple exponential law; this happens when the charge contained in the avalanche reaches a certain value, and the space charge effects due to the presence of the ions in the avalanche cannot be neglected any more. This saturation effect leads to a reduction of the electric field experienced by the electrons contained in the avalanches; it is already known and reported in literature, even if for different detector and electric field configurations [5].

To include the saturation effects in the simulation we have followed the simple mechanism proposed in [3]; this consists in letting an avalanche grow exponentially until the charge contained in it reaches a given value q_{sat} ; then, in a crude approximation, the avalanche stops its development, and just drifts towards the anode.

In this case expression (2) has to be modified to take into account the two different phases: exponential growth and drift. Let us define the saturation length x_{sat} as:

$$x_{sat} = x_0 + \frac{1}{\eta} \log \left(\frac{q_{sat}}{q_e n_0} \right) \quad (6)$$

obtained computing the distance an avalanche has to travel to grow up to the saturation charge

q_{sat} . If $x_{sat} < g$ the charge induced by one cluster is given by:

$$q_{ind} = \frac{q_e}{\eta g} \Delta V_w n_0 M \left[e^{\eta(x_{sat}-x_0)} - 1 \right] + M \Delta_w \frac{g - x_{sat}}{g} q_{sat} \quad (7)$$

the second term arising from the simple drift of the saturated avalanche toward the anode. If $x_{sat} > g$ the saturation actually does not happen, and expression (2) is still valid.

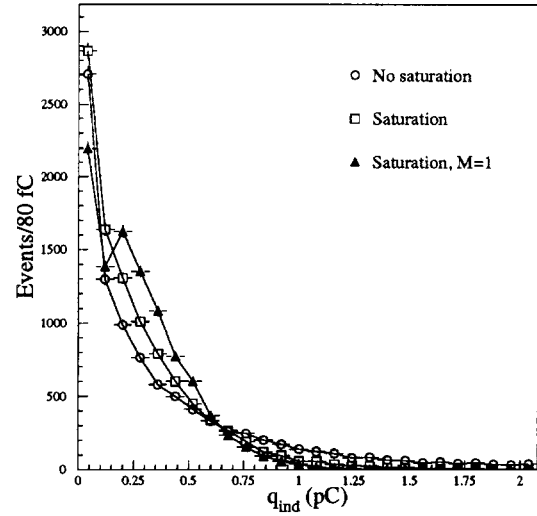


Figure 4. Comparison between charge spectra with and without saturation effects included, for $\eta = 9 \text{ mm}^{-1}$.

Charge spectra obtained with a full simulation of the detector (see, for a complete description, [4]) for $\eta = 9, 10.5, 12$ and 13 mm^{-1} are reported in Fig. 4, 5, 6, and 7 respectively. Here q_{sat} has been chosen to be 2 pC, corresponding to $1.2 \times 10^7 e^-$, close to the Raether limit for avalanche-streamer transition. In each plot three cases are considered for comparison. The first is the charge spectrum obtained not taking into account the saturation effects; the second is obtained by making use of formula (7); the third is

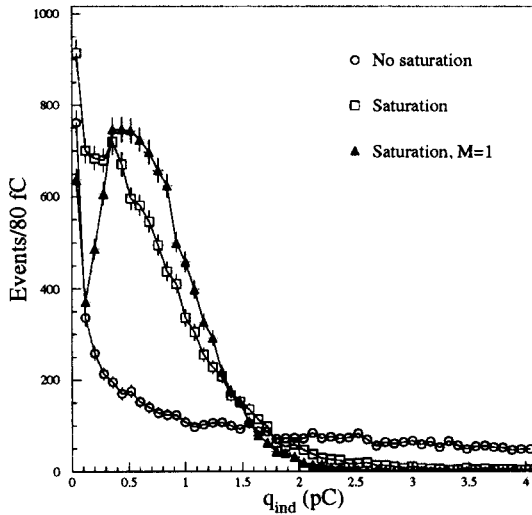


Figure 5. Comparison between charge spectra with and without saturation effects included, for $\eta = 10.5 \text{ mm}^{-1}$.

still obtained with (7), but now the fluctuation factor M is not allowed to vary, and is kept fixed at 1. The third possibility is not unreasonable: all the models accounting for avalanche fluctuations reported in literature refer to a regime of small, or medium-sized, avalanches. Here, at the limit to streamer transition, these models could be no more applicable; as a matter of facts, charge spectra obtained taking $M = 1$ are the closest to the experimental data. Polya-type fluctuations, in fact, tend to “attach” charge spectra to the origin, while experimental data show spectra well detached from it.

When saturation effects are taken into account, a broad peak in the right side of the distributions appear, more and more evident, and shifts to the right, as the operating voltage increases. The actual average value of the peak depends on q_{sat} ; different quenching properties of different gas mixtures could lead to a range of possible values for q_{sat} and explain the differences reported in literature. Eventually, when η is sufficiently high, the fraction of events outside this peak and near the origin is almost negligible. This is exactly the behaviour observed experimentally

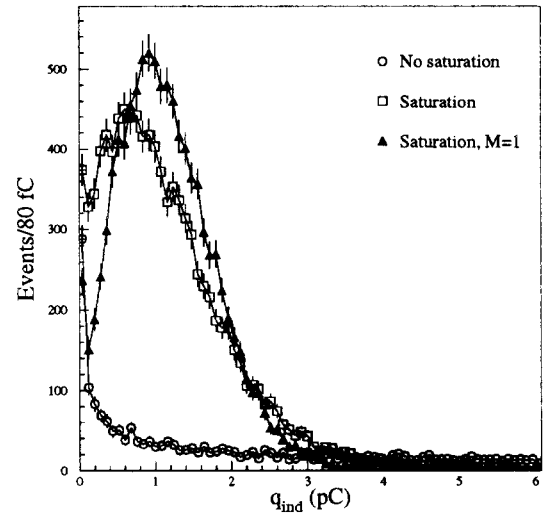


Figure 6. Comparison between charge spectra with and without saturation effects included, for $\eta = 12 \text{ mm}^{-1}$.

[2] [3]. When $M = 1$ the peak is much more evident. The simulation reproduces well the experimental data; however, again high η values are required.

A more elaborate way to perform the simulation would be to compute the actual total electric field acting on the electrons, that means the external one and the one due to the ions. The next step, then, would be to compute again the value of the first Townsend coefficient, in the real conditions (obviously it should be lower than the one due to the external field), and let the avalanche develop accordingly to this effective η value. This part of the simulation is still in progress and will be reported in a future paper. However, this procedure needs the knowledge of the diffusion coefficient of electrons and ions in the considered gas mixture, and the dependence of η on the applied voltage. Both these quantities are not known experimentally for the mixtures generally employed in RPCs.

Finally, it is to be pointed out that correlations among various cluster could modify the observed charge spectra. For instance, the ionic electric field in a given avalanche tend to reduce the one

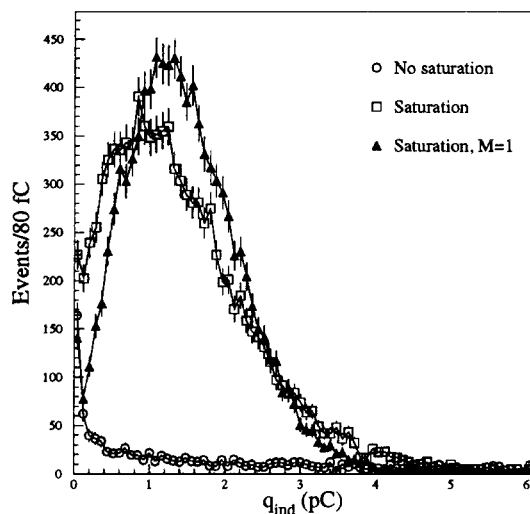


Figure 7. Comparison between charge spectra with and without saturation effects included, for $\eta = 13 \text{ mm}^{-1}$.

for the subsequent, and to enhance the one for the preceding. The maximum effect is on the first cluster, which, therefore, sees a much bigger electric field. This could cause a shift toward the right tail of the charge distribution. The sheet of ions, anyway, is localized in a thin layer $\sim 100 \mu\text{m}$ thick near the cathode, so more refined calculations are needed to understand if this effect is important or not.

4. CONCLUSIONS

Even if the understanding of the charge spectra of Resistive Plate Chambers is a complex argument, and many different effects have to be taken into account, some steps toward the right direction have been taken. The fact that single gap 2 mm RPC reach a full efficiency seems to imply that the primary generation follow more complex schemes than believed, involving electron extraction from the electrodes, for instance. Space charge effects, even in this simplified version included here, can account for the formation of the broad peak in the charge distribution. The simulation, therefore, demonstrate, once more, to be

a powerful instrument to understand the physics mechanisms underlying RPC operation.

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