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The physics of Resistive Plate Chambers

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Abstract

Over the last 3 years we investigated theoretical aspects of Resistive Plate Chambers (RPC) in order to clarify some of the outstanding questions on space charge effects, high efficiency of small gap RPCs, charge spectra, signal shape and time resolution. In a series of reports we analyzed RPC performance including all detector aspects covering primary ionization, avalanche multiplication, space charge effects, signal induction in presence of resistive materials, crosstalk along detectors with long strips and front-end electronics. Using detector gas parameters entirely based on theoretical predictions and physical models for avalanche development and space charge effects we are able to reproduce measurements for 2 and 0.3 mm RPCs to very high accuracy without any additional assumptions. This fact gives a profound insight into the workings of RPCs and also underlines the striking difference in operation regime when compared to wire chambers. A summary of this work as well as recent results on three-dimensional electric field distributions inside the avalanches are presented.

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Keywords: RPC; Simulation; Efficiency; Time resolution

1. Introduction

This report is a short summary of results on Resistive Plate Chambers (RPC) simulations that we published in several reports [1–7]. The motivation for the work was the fact that, until recently, there were still several open questions about RPC detector physics, especially for narrow gap RPCs: e.g., the measured efficiency of 75% for 0.3 mm. Timing RPCs using pure isobutane [8] requires a primary ionization density of about 100 clusters/cm together with a Townsend coefficient of 1000/cm [1]. A 'popular' number for the ionization density in isobutane is however 46 clusters/cm [9]. With such a low number there is no way to arrive at an efficiency of 75% for a realistic threshold of a few fC. Even if the number of 100 clusters/cm were correct, the necessary Townsend coefficient of 1000/cm would result in avalanche charges of 10^7 pC while one measures <5 pC. Early on there were speculations about space charge effects in RPCs [10], but doubts have been raised whether such a strong space charge suppression is indeed possible [11]. In order to solve these problems, 'more complex schemes than believed' like 'electron extractions from the cathode, or photoionisation in the gas' were quoted to be very likely [12]. In our opinion the detector physics of RPCs does not deviate from the

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well-known processes since we consider the number of 100 clusters/cm correct and since the detailed simulation of the space charge effect showed that the small avalanche charges are indeed reproduced. In this report we focus on RPCs with 0.3 mm gas gap since there the space charge effects are much more prominent than in RPCs with 2 mm gas gap.

2. Primary ionization

Primary ionization densities for several gases as calculated with Heed [13] are shown in Fig. 1. This program indeed predicts a number of about 10 clusters/mm for highly relativistic particles. The numbers also agree very well with measurements from Ref. [14]. They are in sharp disagreement with numbers of 4.6 and 1.6 cl/mm for isobutane and methane from [9]. We prefer the large numbers since they solve all the RPC puzzles mentioned before. For a 7 GeV Pion we expect an average distance of $\lambda = 105$ μm between clusters. Heed predicts an average number of $n_{av} \approx 2.7$ electrons per cluster for the $C_2F_4H_2$ gases.

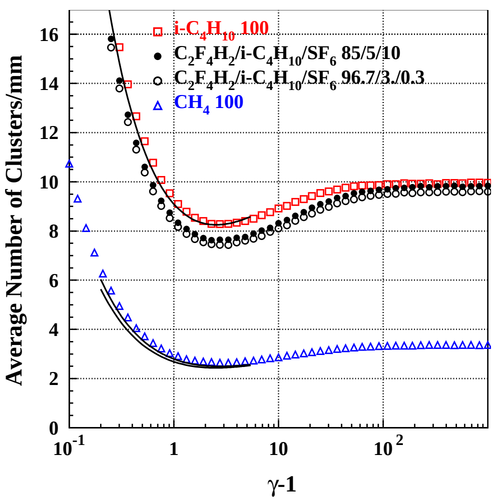

Fig. 1. Average number of clusters/mm for different gases at 296.15 K and 1013 mbar as predicted by Heed [13]. The solid lines show measurements for methane and isobutane from Ref. [14].

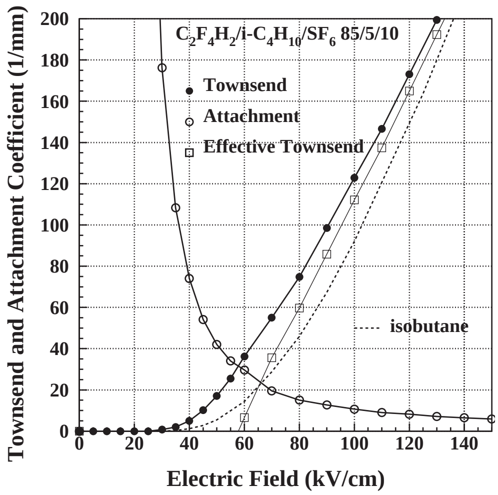

Fig. 2. Townsend and attachment coefficient as calculated by IMONTE [15] for $T = 296.15$ K and $P = 1013$ mbar.

3. Avalanche multiplication

Townsend and attachment coefficients for isobutane and a popular $C_2F_4H_2$ gas mixture for Timing RPCs as predicted by IMONTE [17] are shown in Fig. 2. Typical operating fields of narrow gap RPCs are 100 kV/cm, so we find a Townsend coefficient $\alpha \approx 113$/mm and attachment coefficient $\eta \approx 13$/mm. For simulation of avalanche fluctuations we use a model given in Refs. [1,16].

4. Driftvelocity

The driftvelocity for isobutane and several $C_2F_4H_2$ gas mixtures as predicted by MAGBOLTZ [17] is shown in Fig. 3. For a field of 100 kV/cm we expect a number of $v \approx 210$ μm/ns.

5. Approximate results

In order to find out if the above gas parameters give RPC performance numbers close to experimental ones we can use some approximate formulas. The RPC efficiency is approximately

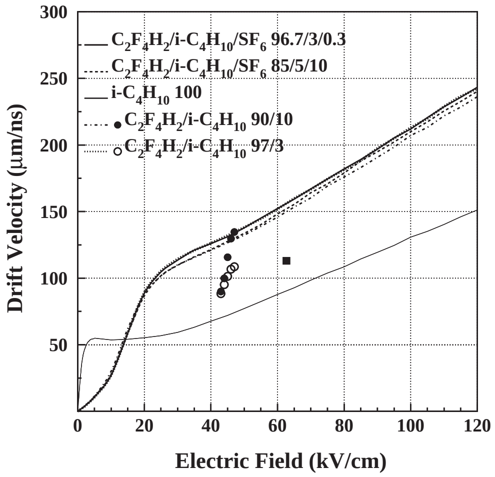

Fig. 3. The lines show the drift velocity for different gases at 296.15 K and 1013 mbar as predicted by Magboltz [17]. The circles show measurements from Ref. [18].

given by [1]

$$\varepsilon = 1 - e^{-(1-\eta/\alpha)\, d/\lambda}\left[1 + \frac{V_w}{E_w}\frac{\alpha-\eta}{e_0}Q_t\right]^{1/\alpha\lambda}, \tag{1}$$

where d is the gas gap, E_w/V_w is the weighting field of about 1.48/mm and e_0 is the electron charge. For a gas gap of 0.3 mm and a threshold of $Q_t =$ 20 fC we find an efficiency of 73% which is quite close to the measured values.

The RPC time resolution is approximately given by [1]

$$\sigma_t = \frac{1.28}{(\alpha-\eta)v}. \tag{2}$$

For the given values of $(\alpha - \eta) = 110$/mm and $v =$ 210 μm/ns we find $\sigma_t = 54$ ps which is close to measurements. The average induced charge is given by

$$\bar{Q}_{ind} \approx \frac{E_w}{V_w}\frac{n_{av}e_0}{\lambda(\alpha-\eta)^2}e^{(\alpha-\eta)d} \tag{3}$$

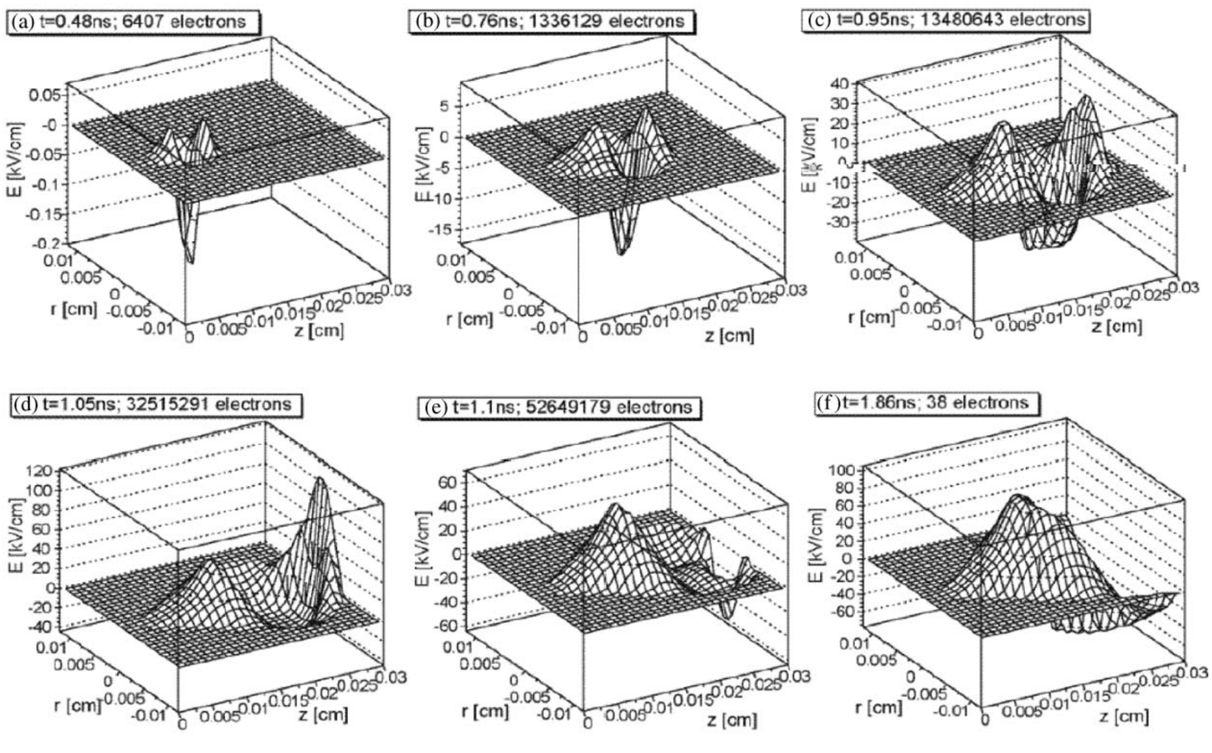

Fig. 4. Development of the electric field within an avalanche in a 0.3 mm gap RPC. The fields are increased at tip and tail of the avalanche, in the center the field is reduced. Note that in the final stage of the avalanche the field due to the space charge approaches 100 kV/cm which is equal to the applied field.

and the average total avalanche charge is given by [1]

$$Q_{\mathrm{avalanche}} \approx \frac{e_0 n_{\mathrm{av}} \alpha}{\lambda(\alpha-\eta)^2} \mathrm{e}^{(\alpha-\eta)d}. \quad (4)$$

Plugging in the above gas parameters we find a number of $Q_{\mathrm{avalanche}} \approx 10^7$ pC which is in sharp contrast to the measured number of about 4 pC. Monte Carlo simulation of the RPC detector performance also gives numbers for efficiency and time resolution that are close to measurements, while the simulated charges are off by several orders of magnitude [1]. In order to investigate this difference we performed a detailed simulation of the space charge effect in RPCs.

6. Space charge effects

Starting from the analytic solution for the electric field of a point charge in an RPC [6] we simulated the space charge effect by dividing the avalanche development into time steps and calculating at each time the electric field distribution within the avalanche and finding locally the gas parameters [2]. As an example, Fig. 4 shows the electric field development within the avalanche of a 0.3 mm gap RPC. At the tip and the tail of the avalanche the electric field is increased, while in the center of the avalanche the electric field is decreased. Most of the electrons are sitting in the center of the avalanche and because of the low field they experience only little multiplication or get attached forming negative ions. Although the electric fields at the tip and tail of the avalanche reach almost twice the applied electric field value and therefore result in very large Townsend coefficients, the effect on the avalanche is small since there are only very few electrons in these regions. A comparison between measured and simulated charge spectra is finally shown in Fig. 5. The simulation indeed reproduces the observed small charges of a few pC.

7. Conclusions

We have simulated RPCs using 'standard' detector physics and find good agreement with measurements for efficiency and time resolution.

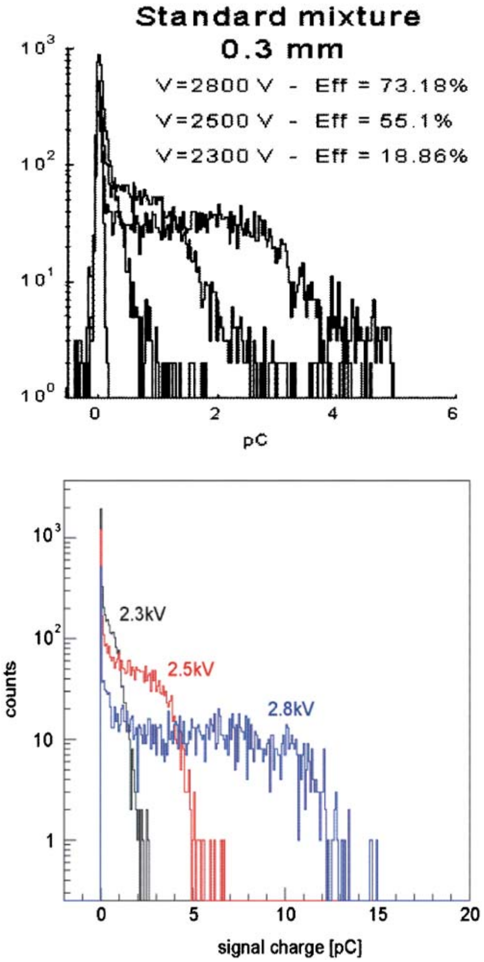

Fig. 5. Measured (top) and simulated (bottom) charge spectra for a 0.3 mm RPC [8] for $C_2H_2F_4$ gas mixture from Fig. 2.

Neglecting space charge effects results in numbers for avalanche charges that are several orders of magnitude larger than experimental values. The detailed simulation of the space charge effect however explains the small measured charges of a few pC. We therefore conclude that the detector physics of RPC do not deviate from the well-known processes, space charge effects are however very strong in this detector.

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