Published by IOP Publishing for Sissa Medialab

Received: *May 21, 2016*
Accepted: *September 23, 2016*
Published: *October 3, 2016*

13th Workshop on Resistive Plate Chambers and Related Detectors,
22–26 February 2016,
Ghent, Belgium

2016 JINST 11 C10001

Improving rate capability of Resistive Plate Chambers

Marcello Abbrescia

Dipartimento di Fisica, Università di Bari, and Sezione INFN
via Amendola 173, 70126 Bari, Italy

E-mail: marcello.abbrescia@ba.infn.it

Abstract: The High Luminosity phase of Large Hadron Collider, foreseen to start in less then ten years from now, has triggered the development of a new generation of gaseous detectors with much improved performance with respect to the present ones. For what concerns Resistive Plate Chambers (RPCs), research is focusing on the methods to increase their rate capability, i.e. the maximum flux of impinging particles that these devices can stand without losing efficiency for a prolonged period of time.

Different solutions are being proposed and extensively investigated upon. Here a brief overview of the physics processes taking place in RPCs at high rate is presented. The fundamental parameters that influence rate capability are taken into exam and the way how they can be optimized in order to increase rate capability is outlined. A comparison between the models used and experimental data confirms the goodness of the approach and the validity of results obtained.

Keywords: Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Resistive-plate chambers

doi:10.1088/1748-0221/11/10/C10001

Contents

1 Introduction

Resistive Plate Chambers (RPCs in the following) are used in the muon systems of three of the big experiments at the Large Hadron Collider (LHC), i.e. ALICE, ATLAS and CMS. These systems were originally designed to operate for about ten years at the nominal LHC luminosity, planned to reach a maximum around $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

With the decision to prolong the operational lifetime of LHC and to increase its luminosity, during the so called High Luminosity phase of LHC (HL-LHC), these systems have to be improved in order to provide at least constant performance in a much harsher environment. In some cases, additional chambers will be installed, often in regions characterized by a quite intense background.

In this context, the need for an increased RPC rate capability plays a crucial role. Rate capability is defined as the maximum flux of impinging particles that can be revealed by these devices without significant efficiency degradation.

Here the detector fundamental parameters that influence rate capability will be taken into exam, and some possibilities about how they can be optimized in order to increase rate capability will be outlined. Two models will be taken into consideration: a simple "ohmic" model, and a more refined "dynamic" one, implemented also using a full Monte Carlo simulation.

2 The "ohmic" model

At high rate RPC efficiency degrades because, being them resistive devices by definition, they are characterized by a time constant which determines the time needed for an electrode to be charged up again, after that the avalanche following the passage of an ionizing particle has partially discharged it. If this time is too long, the subsequent particle crosses the gas gap when the electric field in the gas is reduced in intensity with respect to its nominal value; consequently, there is a higher probability for the associated signal to be under threshold, hence partial inefficiency.

Many discussions are currently taking place in the RPC community, about the best methods to describe what happens in RPC at high rate, and the possibilities to improve their rate capability. Generally the approach is not to consider all the complex processes outlined above, but perform a drastic time average and take into account just the ohmic drop ΔV_{el} due to the current I which is flowing through the electrodes; the fact that, at high rate, ΔV_{el} may be no more negligible with respect to the voltage nominally applied to the electrodes ΔV_{appl} accounts for an efficiency decrease [1].

In this framework, the voltage drop ΔV_{gas} in the gas gap is given by: $\Delta V_{gas} = \Delta V_{appl} - \Delta V_{el}$, which, in explicit form can put as:

$$\Delta V_{el} = RI = \rho \frac{2d}{S} \Phi S \langle Q_{aval} \rangle = 2\rho d \Phi \langle Q_{aval} \rangle \tag{2.1}$$

where R is the electrode resistance, ρ is the resistivity of the electrodes material, d is the thickness of each plate (here we consider the simplest case, i.e. single gap RPCs), S their surface, Φ the flux of impinging particles (in Hz/cm^2) and $\langle Q_{aval} \rangle$ the average charge in the gas gap related to the avalanche processes associated to each impinging particle. Of course, for an RPC to be efficient at high rate, ΔV_{el}, is to be kept negligible with respect to ΔV_{appl} as much as possible, even under heavy irradiation.

This approach is quite simple from the conceptual point of view, but has the disadvantage that it is not possible to directly compute RPC rate capability. One has to measure the efficiency curve at low rate, then compute ΔV_{gap} at the desired rate by using the above formulas, and infer the efficiency at that rate from the efficiency measured at low rate at the same ΔV_{gap} just computed, taking into account that ΔV_{appl} could be in principle quite different at low and high rate.

Basically, ΔV_{gap} is the driving parameter, so that plotting the efficiency curves taken at different rates, versus ΔV_{gap} (and not ΔV_{appl}), should make them coincide all. This was done quite successfully, for instance in [2].

Anyhow, some deductions can be drawn using the above simple model. If, given a certain flux of impinging particles, ΔV_{el} has to be kept as low as possible, the possibilities evidenced by equation (2.1) are to reduce either the electrode resistivity ρ, or their thickness d, or the average induced charge $\langle Q_{aval} \rangle$, or whatever combination of these factors.

Electrode thickness in the bakelite RPCs used at the LHC experiments is 2 mm, which, for future chambers, could be in principle reduced down to around 1 mm (beyond which probably issues related mechanical rigidity could come into play), providing up to a factor 2 reduction for ΔV_{el}, with a subsequent increase (not easy to evaluate) in rate capability.

Electrode resistivity for the same RPCs is around $1 \div 6 \; 10^{10}$ Ωcm, and could be reduced by order of magnitudes, the main drawbacks being manufacturing issues of the materials, and that RPCs, below a certain resistivity, tend to generate spontaneous micro-discharges, with corresponding dark current and counting rate increases. Anyhow, a factor 5 or 10 could be easily obtained, with a subsequent beneficial reduction in ΔV_{el}.

So, from this model, one should deduce that the potential effectiveness in improving RPC rate capability by reducing electrode resistivity ρ, is in principle much more important than the one related to a reduction of electrode thickness d.

Moreover, here gap thickness g does not seem to play any role at all, as it does not appear in equation (2.1); therefore if future RPCs for the LHC experiments are to be produced with a smaller gap g with respect to the 2 mm currently used, this should be related to reasons different than increasing rate capability.

Finally, a reduction of $\langle Q_{aval} \rangle$ is also a way to increase RPC rate capability. However, since a smaller $\langle Q_{aval} \rangle$ also means smaller induced charge on read-out electrodes $\langle Q_{ind} \rangle$, which therefore

2016 JINST 11 C10001

could become lower than the read-out electronic threshold $\langle Q_{\rm thr}\rangle$, this has to be associated with a re-design of the front-end electronics, in a way much similar to what was done in the 1990s, when, passing from the streamer to the avalanche operation mode, part of the gain was transferred from the gas to the front-end electronics. It is quite an effective approach, though, since it reduces also issues related to detector aging, typically proportional to the charge integrated during the detector lifetime, and in fact will be likely pursued for the upgrade of some of the muon systems at the LHC experiments.

3 The single-cell dynamic model of RPCs

If a deeper understanding of what really happens in an RPC at high rate is to be achieved, one has to start by using the basic equations describing the physics processes taking place in these devices, i.e. primary ion-electron pairs generation, electrons migration and avalanching, and the corresponding signal induction on read-out electrodes.

It has been shown, for instance in [3], that, under certain approximations, the current $i_{\rm ind}(t)$ induced on read-out electrodes can be written as:

$$i_{\rm ind}(t) = -\mathbf{v_d} \cdot \mathbf{E_w} q_e e^{\eta v_d t} \sum_{j=1}^{n_{cl}} n_0^j M_j \tag{3.1}$$

where q_e is the elementary electric charge, $\mathbf{E_w}$ if the weighting electric field inside the gas gap, $\mathbf{v_d}$ is the electron drift velocity in the RPC gas gap, η if the first effective Townsend coefficient (i.e. the first Townsend minus the attachment coefficient), n_{cl} is the number of clusters in the gas gap generated by the passage of the ionizing particle, n_0^j is the number of electrons initially contained in each cluster, and M_j is a stochastic parameter related to the avalanche gain fluctuations. Here the time t starts at the passage of the impinging particles, and the contribution of each avalanche has to be taken into account only if at the time t the avalanche is still moving inside the RPC gas gap. If saturation effects have to be taken into account, then the avalanche growth, which here is assumed to be exponential, has to be modeled in other ways, for instance, like it has been done in [4].

On top of this picture, the rapid discharging and charging up of the electrodes is modeled using a resistive and capacitive simple network, like the one shown in figure 1, also used in [5], and already proposed in [6]; the time constant τ associated with this circuit can be expressed as:

$$\tau = 2R\left(\frac{1}{2}C_{\rm el} + C_g\right) = 2\rho\epsilon_0\left(\frac{1}{2}\epsilon_r + \frac{d}{g}\right) \tag{3.2}$$

where R and ρ are the electrodes resistance and resistivity, $C_{\rm el}$ the electrode and C_g gap capacitance, respectively, ϵ_0 the vacuum dielectric permittivity and ϵ_r the electrode dielectric constant and other symbols have already been defined earlier on. This circuit represents just a small portion of the electrode plates, in correspondance of the footprint of the avalanche disk as it touches the anode. In this case, for simplicty, it has been considered as having a 1 mm^2 area, which is greater than the actual area of an avalanche disk, and which has been chosen to roughly account for the currents flowing along the bakelite surface inside the cell.

The evolution in time of $\Delta V_{\rm gap}(t)$, obtained within this framework using a Monte Carlo simulation, is plotted in figure 2, where also the values corresponding to $\Delta V_{\rm appl}$ and $\Delta V_{\rm gap}$ computed

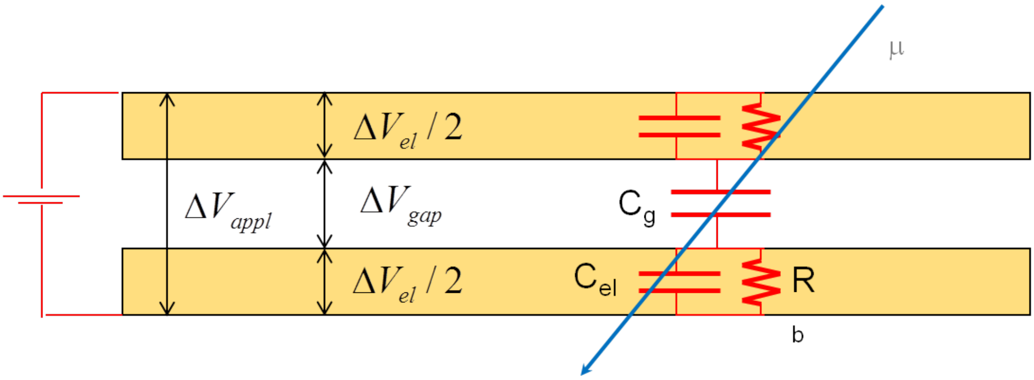

Figure 1. Simple layout and equivalent circuit used to simulate RPC electrode plates discharging and charging up.

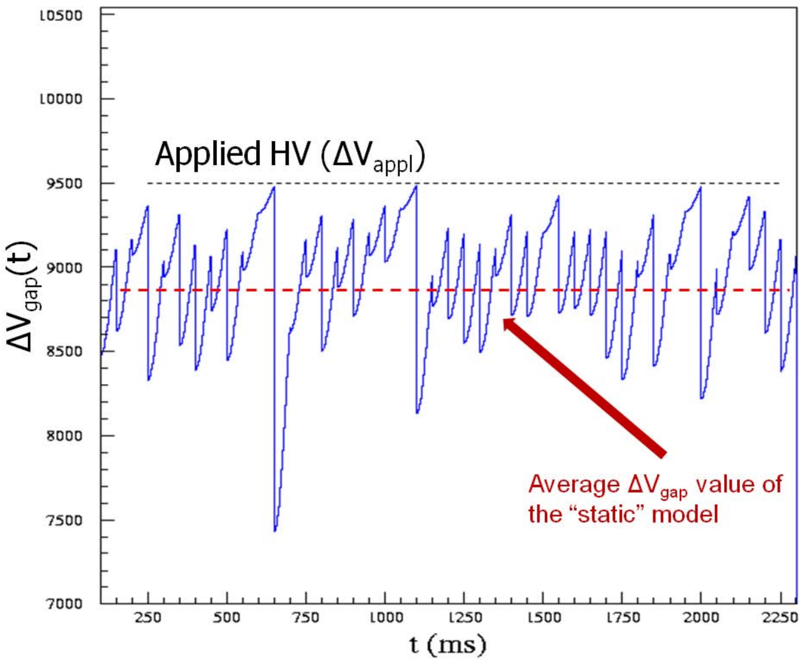

Figure 2. The evolution in time of $\Delta V_{\mathrm{gap}}(t)$, i.e. the instantaneous voltage drop between the two RPC electrode plates. In this particular case, the rate of particles impinging was simulated to be 20 Hz; since the area of the cell was 1 mm^2, this corresponds to, roughly, 2 kHz/cm^2.

with the static "ohmic" model are reported. The picture shows sudden variations of $\Delta V_{\mathrm{gap}}(t)$, and interesting correlations between the amplitude of subsequent signals. There can be a big avalanche (noticed because $\Delta V_{\mathrm{gap}}(t)$ changes abruptly of a remarkable amount) only after a smaller avalanche has taken place, and $\Delta V_{\mathrm{gap}}(t)$ has approached back to its nominal value ΔV_{appl}. These important details are of course lost when using the ohmic approximation described in the previous section.

The "effective" ΔV_{eff}, that is the value of $\Delta V_{\mathrm{gap}}(t)$ at the start of each avalanche, is reported in figure 3 for various values of the frequency of impinging particles. It can be noted that the average ΔV_{eff} reduces as the particle flux increases, as it is expected and as the ohmic model correctly

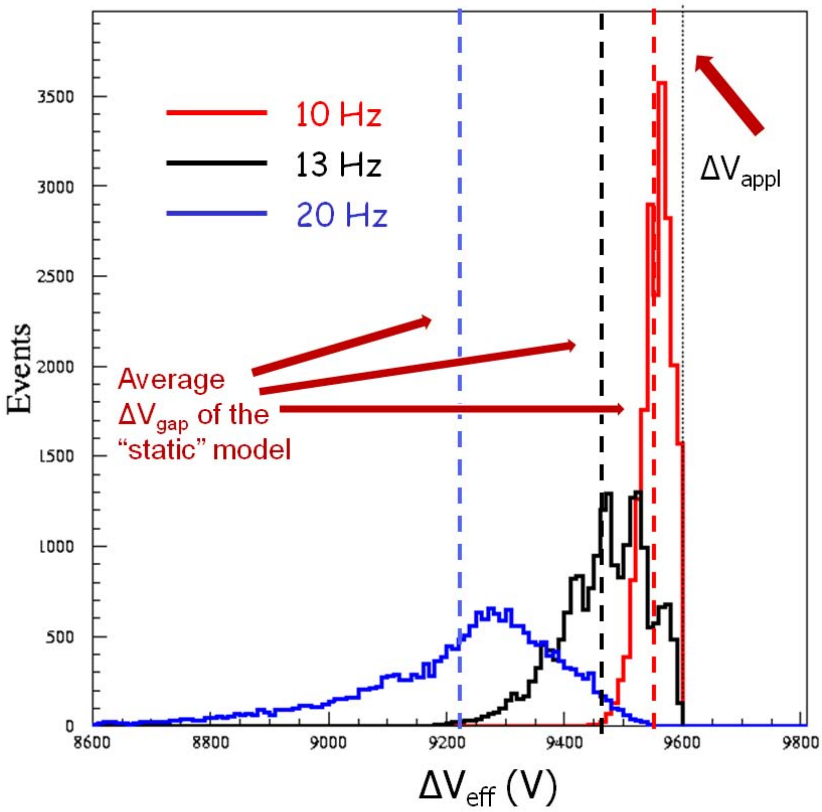

Figure 3. The "effective" ΔV_{eff} as defined in the text, for various values of the rate of impinging particles.

foresees; however, its distribution spreads more and more, which could not be foreseen by the simple ohmic model. In other words, the avalanches at high rate develop in a lower average electric field (with a correspondingly lower gain), but in addition the fluctuations on such a gain increase as the rate increases.

The efficiency at fixed ΔV_{appl} vs. the rate of impinging particles is reported in figure 4, for various values of the electrode resistivity ρ. Here efficiency is computed by integrating equation (3.1) to obtain the distribution of the induced charge Q_{ind} and counting the fraction of events when Q_{ind} is higher than a certain electronic threshold Q_{thr}. This is a direct prediction on rate capability, which is seen to be increasing with a reduction on ρ.

Efficiency at fixed ΔV_{appl} vs. rate is reported in figure 5 as well, but in this case the two curves obtained by the simulation refer to avalanche and streamer events. For the streamer curve, Q_{ind} has been multiplied by a factor ten in order to simulate avalanches beyond the Raether limit, transforming into streamers. This has a relevant effect on rate capability, which is predicted to decrease to values around few hundreds Hz/cm^2; on the same figure, experimental points taken from [7] are superimposed, and they fit nicely with the predictions. This is a direct indication of how an increase of rate capability can be also achieved by farther reducing Q_{aval}, as it was pointed out in the previous section.

Finally, the presence of the factor $\mathbf{v_d} \cdot \mathbf{E_w}$ in equation (3.1) deserves a few words of comment. The weighting field $\mathbf{E_w}$ is well known to depend on the geometry of the system under consideration.

2016 JINST 11 C10001

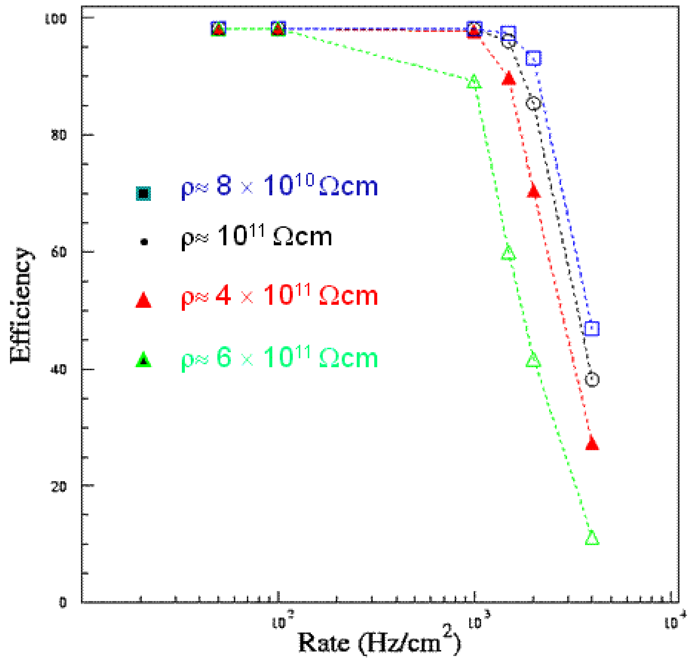

Figure 4. Efficiency vs. rate of impinging particles, at fixed operated voltage, for various values of the electrode resistivity

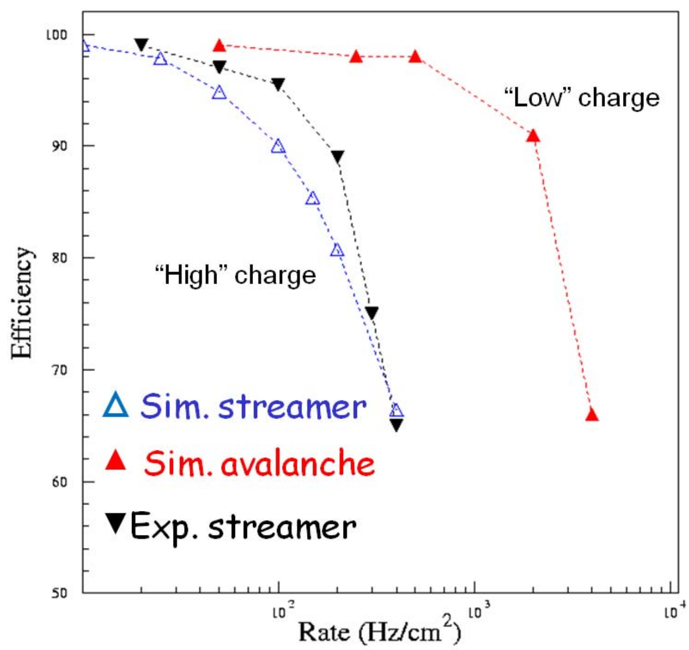

Figure 5. Efficiency vs. rate of impinging particles, at fixed operated voltage, in the cases of induced charge computed starting from equation (3.1), and streamers, with an induced charge ten times higher. Experimental points taken from [7] are also superimposed.

One can compute the weighting field voltage drop ΔV_w in the gas gap, as the integral of $\mathbf{E_w}$ on a path-line perpendicular to the two electrodes. In the case of a single gap RPC, treating the gas gap and the electrodes as three serially connected capacitors, as it was done in [6], this results to be:

$$\Delta V_w = \frac{\epsilon_r g}{\epsilon_r g + 2d} \tag{3.3}$$

Since the charge Q_{ind} induced on read-out electrodes is the integral of $i_{\text{ind}}(t)$, the consequence is that Q_{ind} is proportional to ΔV_w. Therefore, a change in the detector configuration affecting ΔV_w would also affect rate capability since it would change Q_{ind} given the same value of Q_{aval}. Therefore, contrarily to what it has been stated at the end of the last section using the simple ohmic model, on can deduce that changing gap thickness g, by keeping all the rest unchanged does have an effect on rate capability. For instance, reducing it, will reduce Q_{ind} and consequently reducing the rate capability at high rate. On the contrary, rate capability is in general improved if the ratio d/g is kept as low as possible.

4 Conclusions

The two models presented here allow to obtain simple rules on how to improve RPC rate capability; from a qualitative viewpoint, as it was expected, they give similar results since they are, at different levels, descriptions of the same physical processes. The dynamic "single cell" model is a better approximation of reality, gives a more complete and accurate description of the parameters determining rate capability, and its predictions are generally experimentally verified. Nevertheless it can be further improved.

As a matter of fact, this model of the behavior of an RPC at high rate, even if "dynamic", is still local, in the sense that just the zone immediately corresponding to the avalanche development is taken into account. One should also consider that the process of charging up the discharged cell takes place not only with a current flowing perpendicularly to the electrode plates, but also transversely. In bakelite RPCs, as the ones explicitely considered here, there is the added complication deriving from the fact the the electrodes are coated with a thin layer of polymerizhed linseed oil, and this should be considered when studying surface currents. Therefore another parameter of the electrode material(s) should be taken into account, i.e. electrode surface resistivity, which would play a role determining the fraction of the current which actually flows on the electrode surface.

Moreover, a more refined approach would also probably describe the local components of the electric field and give interesting information about the dimension of the cell involved in the charge-discharge process, which, at the moment, is a parameter that has to be put by hand. All these possible improvements are a nice exercise that could help understand even in more details what happens in an RPC at high rate.

References

[1] R. Santonico, *RPCs for high radiation environment*, presentation given at the *Second ECFA workshop on HL-LHC*, Aix-les-Bains, 21-23 October 2014.

[2] G. Carboni, S. De Capua, D. Domenici, G. Ganis, R. Messi, E. Santovetti et al., *A Model for RPC detectors operating at high rate*, *Nucl. Instrum. Meth.* **A 498** (2003) 135.

[3] M. Abbrescia et al., *The simulation of resistive plate chambers in avalanche mode: Charge spectra and efficiency*, *Nucl. Instrum. Meth.* **A 431** (1999) 413.

[4] M. Abbrescia et al., *Progresses in the simulation of Resistive Plate Chambers in avalanche mode*, *Nucl. Phys.* **B 78** (1999) 459.

[5] M. Abbrescia, *The dynamic behaviour of Resistive Plate Chambers*, *Nucl. Instrum. Meth.* **A 533** (2004) 7.

[6] R. Santonico, *RPC: status and perspectives*, *Scientifica Acta* **VIII** (1993) 1.

[7] ALICE collaboration, *Study of the resistive plate chambers for the ALICE dimuon arm*, *Nucl. Instrum. Meth.* **A 456** (2000) 73.

[8] R. Santonico, *Topics in Resistive Plate Chambers*, *Scientifica Acta* **XI** (1996) 1.