Rate Effects in Radiation Detectors with Resistive Electrodes

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Abstract

Detectors with highly resistive electrodes, particularly RPCs, have been studied extensively in recent years. Several authors considered the effect of rate on the detector response (efficiency) and a few also associated with the rate, in a rather qualitative manner, the charge per event, i.e., the current. Here, without loss of generality of the results obtained, rate effects are studied with a classical cylindrical counter geometry and different gas mixtures. To a high accuracy, the observed behavior, both for the proportional mode and for the transition to streamers, is quantitatively and accurately interpreted as loss of voltage on the dielectric due to the current generated in the detector, with direct consequences for the local electric field in the avalanche region. Results obtained in the self quenching streamer (SQS) mode fail the previous interpretation and clearly need further research.

I. INTRODUCTION

Detectors with highly resistive electrodes have been studied for several years. More than two decades ago experimental data were obtained using strips and wires in contact with insulators [1]. Later developments are the very successful resistive plate chambers, RPCs, introduced by Santonico [2], and the more recent MSGCs, proposed by Oed [3]. In some devices the highly resistive electrode is essentially a suitable support for the metallic micro-structures, whereas in others it has a very important and active role, allowing the use of very high voltages, thus featuring very fast time responses with low dark current and without breakdown. In recent papers [4-6] as well as in an old one [1] the resistive electrode may have both roles. The more recent work on RPC detectors deals, in particular, with the study of rate effects, and their operation in the proportional and streamer regions, the research on the effect of high concentrations of UV absorbing gases and the use of narrow and wide size gaps (see [7-10]). In this work we consider mainly the rate effects associated with the gain and/or the efficiency of detectors with resistive electrodes.

For such a study, it was decided to use the classical proportional counter geometry, with a resistive cylindrical tube as the cathode, rather than the parallel plate geometry. The generality of the information obtained is not affected and indeed the proportional counter geometry has advantages, as it allows good energy resolution, i.e., the detection and measurement of small variations of gain and a very good definition of the regimes of operation (proportional, saturated and self quenching streamer (SQS) mode). To our knowledge, previous estimates were never associated with direct measurements of the voltage across the gas, and did not compare results obtained with resistive detectors with all-metal devices of alike geometry.

The present technique relies on the direct comparison of data obtained in detectors fitted with resistive electrodes and in a metallic detector which has exactly the same geometry and operates under the same conditions (gas mixture, high voltage, read-out electronics, etc.). This ensures a direct measurement of the voltage across the gas and the errors introduced are small.

Previous results [11,12] showed that the loss of pulse height that is observed when such a resistive detector is operated under increasing detector current can only be ascribed to the reduction of the effective voltage difference across the gas. Indeed, as a consequence of the resistance of the lossy dielectric that constitutes the cathode, the voltage applied is reduced by a predictable amount which can be easily computed under the assumption that the symmetry (homogeneity) of the charge build-up and collection over the cathode surface is maintained.

The motivation for the present work is to study to what extent this interpretative model can be extended to operating regimes where the charges developed in the avalanches are significantly larger, and to consider if the discontinuity associated with the threshold for the transition between the proportional and the streamer mode can similarly be accounted for.

II. THE EXPERIMENTAL SET-UP

The experimental results shown below were obtained with a long cylindrical counter made of glass (ϕ_i = 12.7 mm, wall thickness = 1.1 mm and resistivity $\rho \sim 7 \times 10^{12}$ Ohm.cm) fitted with a stainless steel anode wire (ϕ = 50 μm). As shown in Figure 1, the tube is divided into two sections: one of them was covered externally with a thin grounded layer of *Aquadag*, forming a simple resistive detector, referred to below as RD, while the other was covered internally by the same layer.

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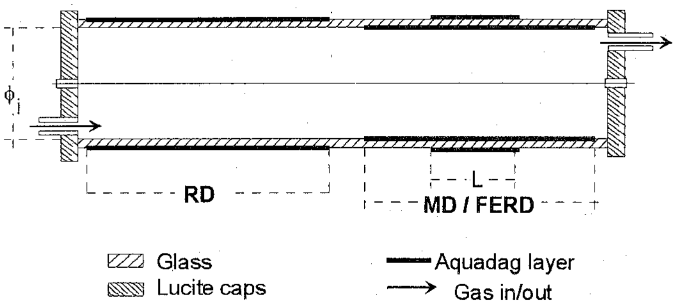

Figure 1: Schematic view of the cylindrical glass detector.

In a small region of the part painted internally, conductive painting was also applied externally for a length *L* of 31 mm and connected to ground. The internal *Aquadag* electrode may be grounded or not. In the first case the tube behaves as a conventional metallic proportional detector and will be designated MD. In the second case the internal cathode is truly floating, i.e., it is not connected externally to any passive or active electronics, and we designate it as the floating electrode resistive detector, FERD.

The Ar/CO_2 (45:55) gas mixture has been used for the measurements related to the transition from the proportional to the self quenching streamer mode, whereas the measurements in the proportional regime were taken with P-10 (argon with 10% CH_4). Other cylindrical geometries (anodes $\phi = 50$ and 127 μm, cathodes $\phi = 12.7$, 13.9 and 31.6 mm, wall thickness of 0.7 and 1.1 mm) and gaseous mixtures (argon/ethane, argon/isobutane in various proportions) have also been tested. However, the results so obtained do not differ significantly from those presented below, which were obtained in a more systematic way. All the measurements were performed at atmospheric pressure and at room temperature.

X-rays from a ^{109}Cd source (22 keV) irradiate the detector through its glass wall. The apparent length of the detector cylinder irradiated (4 to 16 mm) is limited by Pb plates positioned symmetrically in respect to the source. Except for the data shown in Figure 5, this distance is normally fixed and the rate is changed by interposing aluminum plates of appropriate thickness (0.5 to 4 mm) between the source and the detector. The irradiation can therefore be considered roughly uniform in azimuth. In the data shown in Figure 5, the increase of the rate is obtained by increasing the distance between the lead plates. The effective length irradiated is of course different, due to both the opening angle of the beam and the increasing absorption of the X-rays in the absorbers and in the cathode walls with the incidence angle.

The charge spectra were measured using a conventional charge amplifier electronic system and a multichannel analyzer, calibrated using a standard pulse generator. The effect of the amplifier RC shaping networks on charge pulses was taken into account in order to obtain the total mean charge per avalanche. In the proportional mode we used the empirical formula of Mathieson and Charles [13] for equal RC integrating and differentiating networks with a time constant T = 1-2 μs. For the SQS avalanches we used the method described by Lima et al. [14].

III. DATA, ANALYSIS AND DISCUSSION

Because the cathode has a finite conductivity, after applying the high voltage to the anode and in the absence of current flowing through the detector, the internal surface of the RD is at the same potential as the external conducting *Aquadag* layer (grounded), as soon as the stationary state is reached, i.e., upon relaxation of the dielectric. Of course the same happens with the voltage of the floating electrode (FERD).

If, starting at $t = 0$, proportional counter pulses are generated in the detector with the ^{109}Cd X-ray source at a mean rate ν, kept constant, and the total mean charge per event is $Q(t)$, a current of intensity $I(t) = Q(t)\cdot \nu$ flows across the resistive cathode. This results in an increase of the potential of the internal surface of the dielectric observed in the RD section. A similar increase of the potential of the floating electrode is produced if the irradiation is done on the FERD region. As the potential across the dielectric increases, the potential between the anode and the internal surface of the cathode (RD and FERD) decreases until a stationary regime is obtained. However, if the irradiation is made on the MD, the current that flows is constant and given by $I = Q(0)\cdot \nu$, as the conductive internal cathode is grounded. Preliminary measurements of the relaxation of the dielectric under irradiation conditions were performed. A typical curve of the time dependence of the pulse charge amplitude measured with the resistive detector (RD) is shown in Figure 2. This dependence assures a normal behavior for a lossy dielectric. Transient effects are ignored here and have been the subject of previous work [12]. All the data reported below refer to the stationary state.

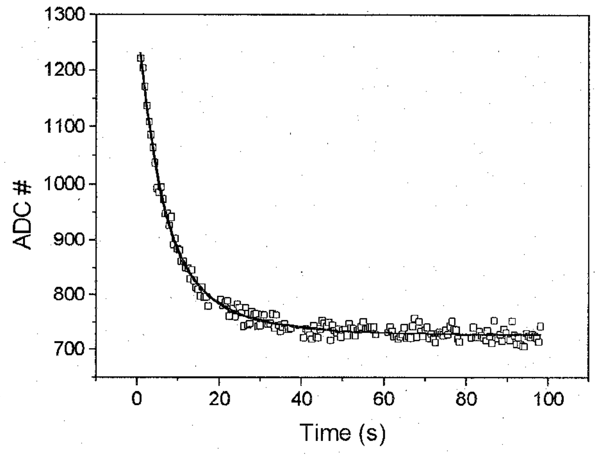

Figure 2: Time dependence of the amplitude of the charge signals for the RD detector. Data were obtained for a counting rate of 240 Hz and an applied voltage of 1700 V, which corresponds to an initial charge gain of about 5×10^4.

A. Proportional mode

The behavior of the resistive detector (RD), operating in the proportional mode under a stationary regime, was reported in a previous work [11]. Similar measurements were performed with the floating electrode resistive detector (FERD). Figure 3 shows the variation with the counting rate of the mean charge amplitude for both the RD and the FERD detectors operating with P-10. These amplitudes are normalized to the one measured with the metallic counter for the same applied voltage (1700 V). We should stress that, for this voltage and for all the rates, there are no space charge effects. Therefore, the gain in the MD remains constant and so the descent of the curves is only due to the drop of gain in the RD and FERD detectors.

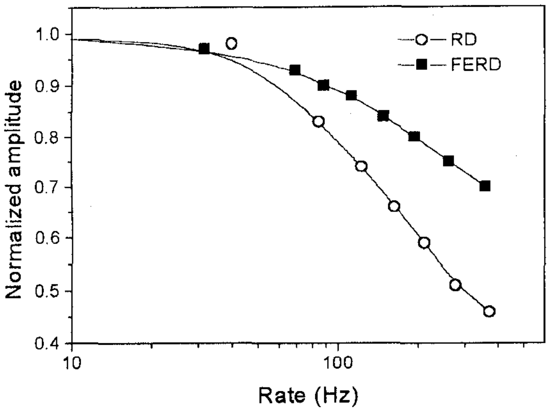

Figure 3: Variation of the mean charge amplitudes with the counting rate for the RD and FERD detectors; these amplitudes are normalized to the one measured in MD detector for the same applied voltage (1700 V). The curves shown are just intended to guide the eye.

The flow of a current $I = Q\,v$ across the resistive cathode results in an increase of the potential of the inner wall of the cylinder given by $\Delta V = IR$ where R represents the resistance of the irradiated part of the glass cylinder. Being h the effective length of irradiation of the RD (this effective length is L for the case of the FERD, independently of the geometry of the irradiation), and having the cylinder inner and outer radii of r_c and r_b, respectively, then $R = \rho \ln(r_b/r_c)/(2\pi h)$. Therefore, the effective voltage difference across the gas when a voltage V_o is applied to the detector reduces to $V_{eff} = V_o - IR$. The determination of V_{eff} is made by registering the voltage for which the pulse height observed in the MD section of the detector equals the pulse height of the RD (or FERD) detector section for a given irradiation rate.

This means that the charge amplitudes represented in Figure 3 correspond to different values of V_{eff} and should be normalized to the value of the charge amplitude measured in the metallic detector for an applied voltage $V_o = V_{eff}$. As it can be observed in Figure 4, when such a correction is applied the normalized mean pulse heights are no more rate dependent proving the correctness of the above interpretation. Not surprisingly, this constitutes a trustful method, as the pulse height is a very sensitive function of V_{eff}. The procedure is even refined by considering the slight difference of radii r_c between the RD (bare glass) and the FERD (or MD) resulting from the thickness of the conductive layer (≈50 μm). Even the estimate of h, that will be mentioned below, relies on the measurement of this effect, avoiding a lengthy Monte Carlo simulation.

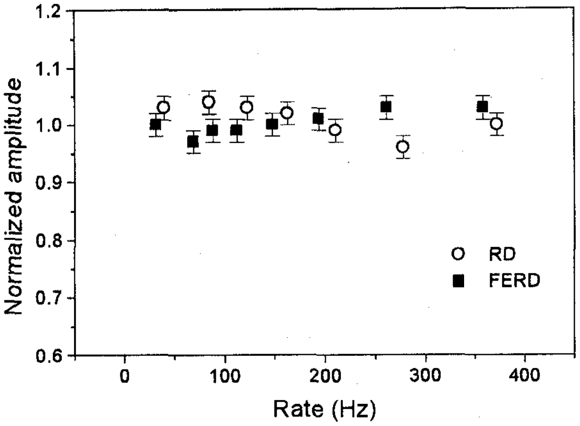

Figure 4: Charge amplitudes measured with the RD and FERD detectors as a function of the counting rate. These amplitudes are normalized to the ones measured with the MD detector for an applied voltage $V_o = V_{eff}$.

In Figure 5 we compare the performance of the RD and FERD sections when the apparent length of the tube irradiated is increased from 4 up to 16 mm. Due to the large area of the floating electrode, a lower resistance is seen by the current that flows in the FERD detector. As a result, the voltage drop, ΔV, is smaller in the latter detector. From the slope of the straight line fit of Figure 5 one computes $\rho = 6.7 \times 10^{12}$ Ω.cm which agrees with the ρ value obtained from electric measurements ($\rho = 6.5 \times 10^{12}$ Ω.cm). The non-linear behavior of the RD curve results from the fact that we are changing both the resistance (by increasing h) and the current.

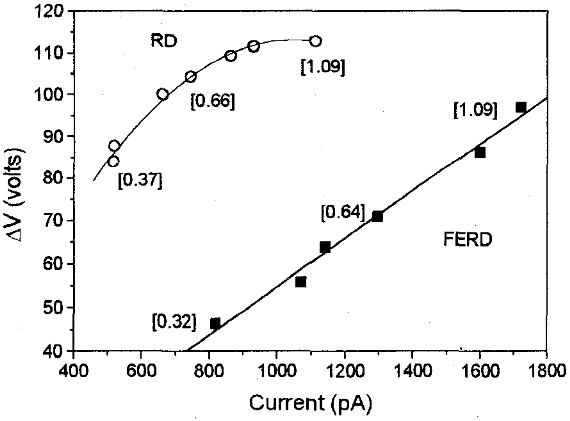

Figure 5: Voltage drop across the glass wall for both RD and the FERD detectors, as a function of the current flowing through the gas. The rates, indicated between brackets, are in kHz. The applied voltage is 1700 V.

B. Transition to streamers

Typical charge spectra in the transition region are shown in Figure 6. As it can be seen, at $V_o = 2850$ V and under a rate of 90 events per second, the FERD detector is clearly above the onset of SQS avalanches, whereas at $V_o = 2950$ V it approaches the conventional transition voltage (i.e., half of the events give rise to proportional/saturated avalanches while the other half develop SQS).

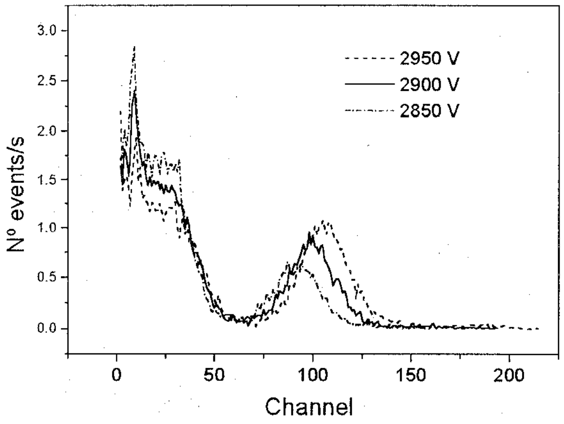

Figure 6: Charge spectra measured with the FERD for three different applied voltages, in Ar+55%CO_2 ($\nu = 90$ Hz).

The mean charges corresponding to the proportional, saturated and the SQS peaks observed both in the MD and the FERD are plotted in Figure 7.a as a function of the applied voltage. Two different event rates are shown for the FERD.

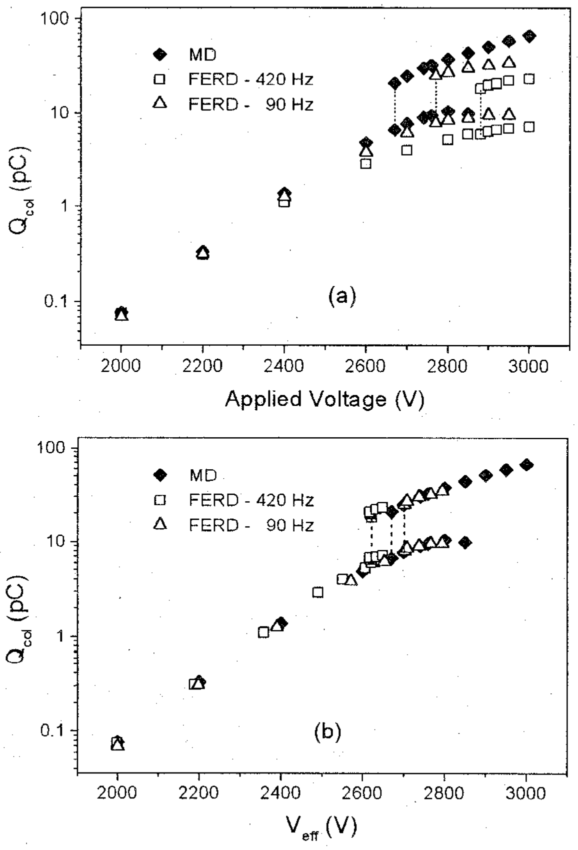

Figure 7: Collected charge, Q_{col}, in Ar+55%CO_2, as a function of: (a) the applied voltage; (b) the effective voltage across the gas, for the MD and the FERD detectors. The dashed lines correspond the applied voltage for which about 1% of the charge pulses were SQS.

The loss of pulse height is clearly visible along the proportional and the saturated regions, being more pronounced for the higher rate. It is apparent that those pulses which do not develop streamers seem to saturate at around 10 pC for the highest voltages tested. The onset of SQS pulses is indicated by the vertical lines connecting two corresponding sets of points. It is clearly visible that the voltage at which the first few percent SQS events develop varies significantly. The development of an SQS avalanche requires a minimum local field in the vicinity of the anode wire. Accordingly, and in qualitative agreement with our model, the onset of the SQS avalanches is situated ≈100 V higher for the FERD operated at 90 Hz than for the MD, and again ≈100 V further for the FERD at 420 Hz. Under the above mentioned assumption, our model can be used to compute the quantitative correction to apply to the data. This was done and the same data are shown in Figure 7.b as a function of V_{eff} (in this case V_{eff} was not obtained by direct comparison with the metallic detector but it was calculated according to the relation $V_{eff} = V_o - RI$). As we can see, the SQS onset on the FERD for the two rates now falls close to the voltage observed for the MD. The observed differences are within the estimated experimental error (1-2%) which is mainly associated with the determination of the total charge per event.

The ratio between the number of SQS pulses and the total number of charge pulses is shown in Figure 7 as a function of the effective voltage for the MD and FERD detectors.

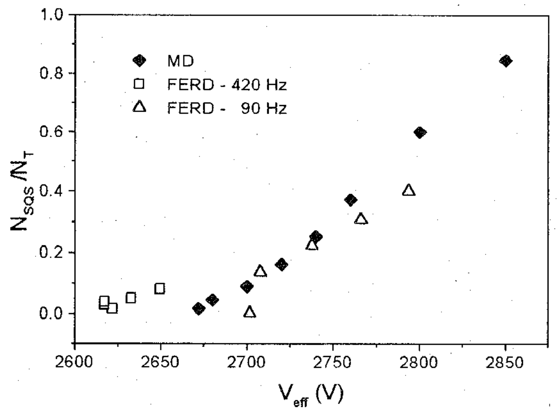

Figure 8: Ratio of the number of SQS pulses and the total number of pulses as a function of the effective voltage for the MD and the FERD detectors.

The maximum values of the applied voltages correspond to the limit above which afterpulses or instabilities (discharges) are observed. The analysis Figure 8 shows that in the resistive detector it is difficult to trigger the SQS pulses especially for the higher counting rate.

The same type of plots are also shown in Figures 9-11 for the case of RD.

Referring to Figure 9 we may remark that the fraction of events developing into SQS in the RD is very small. On the other hand, the definition of the SQS peak is also very poor.

These two observations are compatible with the difficulty in reaching a field around the anode wire strong enough, now that the removal of the charges deposited on the cathode walls is obviously more difficult than in the previous case of the FERD.

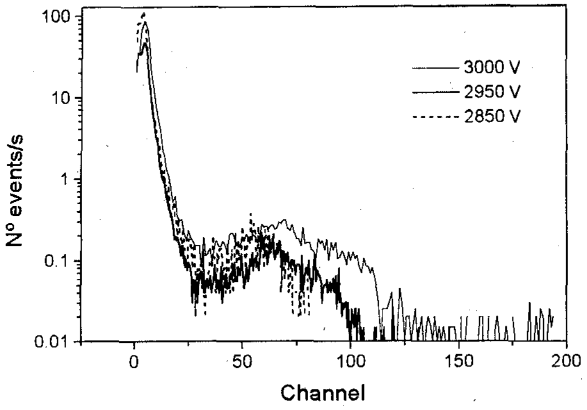

Figure 9: Charge spectra measured with the RD detector for three different applied voltages, in Ar+55%CO_2 (ν = 110 Hz).

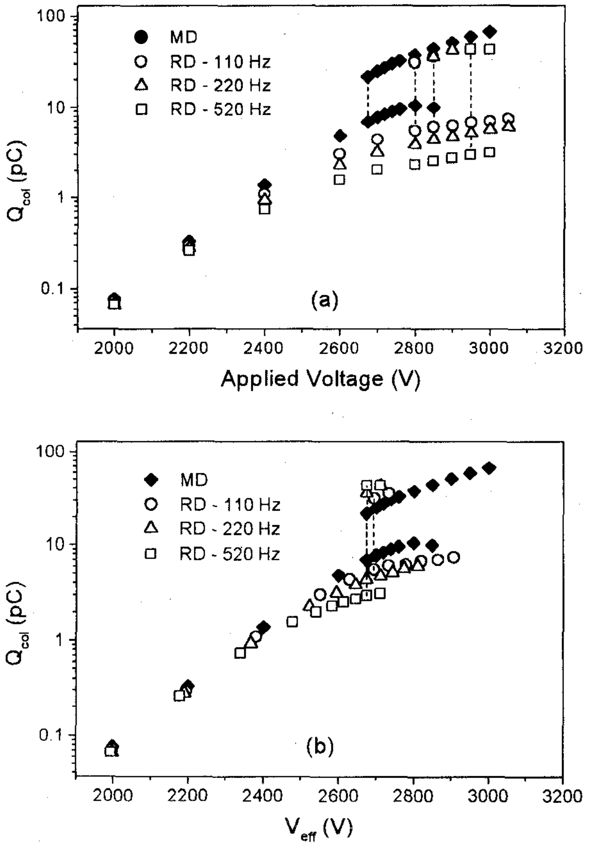

Figure 10: Collected charge, in Ar+55%CO_2, as a function of: (a) the applied voltage; (b) the effective voltage across the gas, for the MD and the RD detectors. The dashed lines correspond the applied voltage for which about 2.5% of the total charge pulses were SQS.

For a comparison of the RD with the metallic detector see Figure 10. Figure 10.a shows a plot of the charge developed in the avalanches as a function of the applied voltage for three different rates. In this case the cylindrical symmetry is lost due both to the low rate of SQS pulses and to the fact that the SQS avalanche is very localized. Therefore the quantitative analysis of this situation is no longer possible. However, as long as the SQS pulses are either non-existent or very rare (<1% of the total charge pulses) the correction for the voltage drop across the dielectric can be performed taking into account only the contribution of the proportional or proportional saturated pulses (see Figure 10.b). Qualitatively, the data present the same general behavior as for the FERD, although the voltage gaps, shown in Figure 10.a, between the onset of SQS in the MD and in the RD are stretched when compared to those observed in the FERD for comparable currents through both resistive detectors.

Figure 11 shows a comparison between the fraction of SQS pulses measured in the MD and RD detectors as a function of the applied voltage. In this case the difficulty in triggering SQS pulses is even greater than in the FERD (see Figure 8). Please note that in Figure 11 the applied voltage is considered because the effective voltage across the gas (see Figure 8) cannot be computed for the cases where the number of SQS pulses is not negligible.

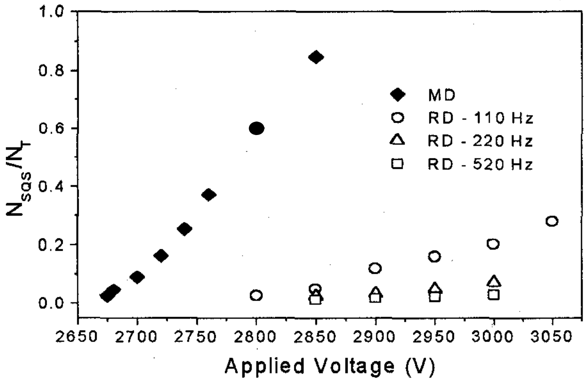

Figure 11: Ratio of the number of SQS pulses and the total number of pulses as a function of the applied voltage for the MD and the RD detectors.

IV. CONCLUSIONS

The results obtained with the resistive detector concerning the gain in the proportional region and the threshold for the transition into the streamer mode agree well with the model proposed, essentially a voltage loss in the dielectric. This was accurately calculated because the experimental conditions were carefully chosen to allow simple and reliable computations. This type of information is practically useful as it can be applied to any type of geometry.

It should be stressed that the model fails if the cylindrical symmetry is lost, and this happens in the RD detector as soon as the streamers start to be seen, on the regions of 1 or 2%. Indeed the charge associated with the streamer is one or two orders of magnitude larger than that of the proportional mode, and it flows through a much smaller area of the cathode (two or three orders of magnitude smaller than for a proportional counter event), seeing then a much larger resistance. To obtain an average cylindrical symmetry in the streamer mode much larger rates than in the proportional regimen must be used. Anyway even at very low rates, under a hundred hertz, we failed to trigger a reasonable fraction of streamers.

Similar general considerations apply for the proportional saturated region, as the corresponding avalanches are more localized than in the proportional region. This effect could clearly be detected comparing the behavior of the data from the FERD (symmetry is assured independently of the mode of operation) and from the RD in the proportional saturated regions, just below the threshold for the transition into streamers.

Once the streamers are triggered their quenching is particularly dependent on the applied field near the tip. It could be thought that the streamers would have a smaller charge in the RD detector than in the metallic one because, apart from the quenching arising from the *1/r* dependence there would be also the usual charge quenching effect as observed in RPCs. In some cases our data seem to contradict this very general remark. However, the large amount of information available from self quenching streamers using all metal cylindrical counters cannot be applied here as the cylindrical symmetry is lost and the streamer charge is obviously dependent on the field behavior over the first 2 or 3 mm away from the anode.

Some of our results considering the streamer mode are far from being explained: to consider this problem the parallel plate chamber geometry, i.e., RPCs, allows much simpler computations. This type of work is under way.

V. ACKNOWLEDGMENTS

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