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Feedback and Breakdown in Parallel-plate Chambers

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Abstract

The existence of a strong connection between the photon feedback and the breakdown phenomena in Parallel Plate Avalanche Chambers (PPACs) is generally accepted. In this work we make a detailed study of these processes in mixtures of Ar and He with CH_4 , C_2H_6 and triethylamine (TEA) vapors. Two breakdown modes (fast and slow) were identified, active for different levels of photon feedback. The breakdown limit (as against the photon feedback) is found to be quite independent from the nature of the filling gas, depending mainly on the total charge in the avalanche. Analytical expressions, based on our measurements, are proposed for the first Townsend coefficient and for the VUV light production coefficient as a function of the electric field and quencher partial pressure. These expressions allow to justify the constant fast breakdown limit on the basis of a space-charge induced electric field distortion. Some results of other authors, concerning a counting rate dependency of the breakdown limit, can also be explained in the framework of this model.

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1. Introduction

The perspective to build high-luminosity hadron colliders, LHC and SSC, is a challenge to detector technology: the detectors should be fast, have high rate capabilities and be radiation resistant. One of the candidates for this purpose is the PPAC, which shows good time resolution (~ 10 ns at atmospheric pressure [1,2] and ~ 150 ps at low pressure [3]), fast collection time (~ 100 ns), high-rate capability (up to 10^5 Counts/s $\cdot$ mm² [4]); there is also indication of tolerance to high radiation doses [5].

Owing to this excellent properties PPACs were proposed recently for crystal calorimetry [6], Ring Imaging Cherenkov (RICH) [7] and for the L^* detector [2], in the future colliders. The PPAC finds application also in slow rate experiments, either with light or pad readout (see for example [8]). Outside high-energy physics, PPACs are used for applications in biology, medicine, astrophysics, etc (see for example [9]).

The main limitations in the operation of PPACs come from feedback and sparking, being generally accepted the existence of a connection between VUV emission from the avalanches, feedback and sparking. On the other hand, in a previous paper [10] we showed that the VUV emission drops sharply with the quencher concentration in the gas, while the breakdown limit remains practically unchanged for the same conditions. In this article we discuss some results of a systematic study of feedback and breakdown in PPACs and its connection with the VUV emission from the avalanches.

2. The experimental setup.

The results presented in this work were acquired using the device described in ref.[10], of which a schematic view is presented in fig.1. It contains two independent gas detectors: a PPAC (10×10 cm²) and a photosensitive wire chamber, separated by a CaF₂ window. The MWPC was used for the VUV emission measurements described in the same ref., the results described here concerning mainly the PPAC part.

The detectors are fed by separate gas systems and can work with different gas mixtures at atmospheric pressure. On the PPAC we used mixtures of argon and helium with TEA vapors, CH₄ and C₂H₆, which are commonly used mixtures for PPACs. The partial pressure of the TEA vapors in the mixture could be regulated from 1 to 50 Torr, and that of CH₄ and C₂H₆ from 6 Torr to atmospheric pressure. The avalanches were initiated using either 5.9 keV X-rays from ⁵⁵Fe or 5.5 MeV α particles from an ²⁴¹Am source. The α tracks were made almost perpendicular to the electrodes by collimation, and a small area of the Mylar window was removed and covered by a 6 μ m thick Hostaphan foil to let the α particles through. The primary charge yield is estimated to be 220 electrons for the X-rays, 5×10^4 for the α particles in Ar gas and 5×10^3 in He gas (from the 11 mm conversion gap).

The electrical circuit used for the readout of the PPAC is schematized in fig.2. Signals were recorded from the PPAC anode by a charge-sensitive amplifier and sent in parallel to an oscilloscope, a pulse-height analyzer and a scaler. The charge amplifier had a long time constant (50 μ s) in order to extend the integration to the ion component of the PPAC signal, thus providing the total charge in the avalanche. The cathode was equipped with a fast current amplifier (10 ns rise and fall time) which,

being faster than the observed avalanche signal slopes, yields an avalanche signal shape (current) relatively unaffected by the readout electronics. Fig.3 shows a test pulse having a 3 ns rise-time superposed to an avalanche current signal, in order to demonstrate the previous statement. The avalanche signal cannot be detected before the electron cloud reaches approximately the last mm of the gap, due to the exponential charge multiplication process. The avalanche rise time corresponds then roughly to the electron drift time in the last mm of the gap and the shorter fall time is thought to be connected with the longitudinal width of the electron cloud. The signals observed have around 30ns rise time corresponding to a drift speed of 3 cm/ μ s, agreeing with the typical values for the electrons drift speed. The fast signal was also integrated with a short time constant (300 ns), providing a measurement of the fast (electron) signal component which is used for the measurement of photon feedback. Both systems are calibrated through the injection of square pulses of current through resistances much larger than the respective input impedances. This method of calibration was preferred to the capacitor method because the calibrating signal approaches better the real signal, providing a more realistic calibration.

3. Feedback

The UV light emission by the avalanches normally produces photoelectrons in the photosensitive elements of the chamber: the metallic electrodes and the gas itself. These photoelectrons originate secondary avalanches following in time the initial one: the so-called photon feedback that affects high rate and photon counting chambers like those designed for RICH applications.

The slowly moving positive ions created in the avalanche can also extract electrons from the cathode when they neutralize there, generating secondary spurious avalanches widely distant in time from the initiating one.

If the contribution of secondaries to the signal is important a number of undesirable effects arise:

- Good localization of the initial avalanche is worsened.
- The signal extends in time more than a single avalanche signal, impairing the rate capabilities of the PPAC.
- A large contribution from secondary processes to the total signal degrades the energy resolution of the counter due to an increase of the number of statistical processes involved in the signal generation.
- The accumulation of successive avalanche generations is a positive feedback process, potentially divergent, that makes the amplification unstable and limits the maximum attainable gain.

In order to understand the influence of these effects on the operation of the PPAC we made a quantitative study of both forms of feedback.

3.1 Measurement of photon feedback efficiency

As we mentioned in a previous article [10], the feedback efficiency in the PPAC could be higher than in MWPCs due to the high electric field near the cathode. We measured the photon feedback efficiency using two independent methods: direct and indirect. Each method extends the measurement to a different range of gases and the comparison of the results obtained checks the consistency of the measurements.

3.1.1 Direct method

This method is based on the simultaneous measurement of both the charge in the initial avalanche and the total charge. The contribution of secondary processes will increase the total charge relatively to the initial charge, providing a measurement of the contribution of secondary avalanches.

The electrical circuit used for this measurement is schematized in fig.2. The current signal taken from the PPAC cathode is fed to a fast current amplifier allowing the visualization of the signal's time structure, as presented in figs.4-6. In parallel the same signal is integrated with a 300 ns time constant, measuring the electron (fast) component of the signal (N_e). The electron component in the initial avalanche is proportional to the signal level at the output of the integrator at a time corresponding to the end of the initial avalanche. The total charge (N_t) is measured by the 50 μ s time constant integrator connected to the anode through a large coupling capacitor.

The direct method of photon feedback measurement depends on a clear identification of the initial avalanche, well separated in time from the successor avalanches. It requires a very localized primary charge deposition, like the one provided by low-energy X-rays (5.9 keV) which, in Ar based gases produces in most cases two photoelectrons, each with a pathlength in the order of 200 μ m. On the other hand, when using mixtures with He the pathlength of the single 5.9 Kev photoelectron is around 1 cm, originating an initial avalanche that is spread in space and time, and a serious limit to the application of this method to He based gases.

The charge in the initial avalanche $N_1 = N_0 G$ can be estimated from the measured electron component through the well known formulas

$$N_e = N_0 G / \ln(G) \quad (1)$$

$$G = \exp(\alpha d) \quad (2)$$

where N_e is the electron component of the signal, N_0 is the primary charge, G is the gas gain, $\alpha(E)$ is the first Townsend coefficient and d is the gap length. A very simple theory due to Townsend relates the total gain in case of feedback to the primary gas gain. If η secondary photoelectrons are produced per electron in the initial avalanche and these secondaries are subject to the full avalanche gain (G), then the relation between successive generations of avalanches is

$$N_1 = N_0 G$$

$$N_{i+1} = N_i \eta G$$

The ratio between the first successor and the initial avalanche is given by $N_2/N_1 = \eta G$. The sum of the geometrical series up to infinite generations yields the total gain

$$\frac{N_t}{N_0} = G_t = \frac{G}{1 - \eta G} \quad (3)$$

The feedback efficiency η is a characteristic of the gaseous mixture, chamber materials and chamber geometry, and might be also field-dependent [10]. The formula above can be inverted to give the feedback efficiency η if both the total gain G_t and the avalanche gain G are known. The measurement should be performed at gains such that ηG is not too small, otherwise the total gain will be equal to the avalanche gain within the experimental precision.

The ratios N_1/N_0 and N_2/N_0 were measured for Ar+TEA and Ar+CH₄ gases at different quencher concentrations; some results are shown in fig.7. The measurements were performed at the maximum gain compatible with a stable operation, discussed in section 5.3. For reduced concentrations of quencher, the contribution of the initial avalanche can be as small as 10% of the total charge. The electrical signal is then relatively extended in time, distributed over several generations of avalanches. In practice the timing characteristics of the PPAC are lost. For quencher concentrations smaller than those presented in fig.7 the initial avalanche becomes undetectable, and we observe only a signal very extended in time (a few μ s). It should be understood that the growth of the current signal in the presence of feedback doesn't necessarily imply that $\eta G > 1$, owing to the contribution of the ionic current (see ref.[11] for details).

The feedback efficiency was calculated from eq.(3) and is shown in fig.8 (solid symbols). For large quencher concentrations the feedback efficiency is usually smaller than 10^{-6} ; the measurements are very erratic below this value, which corresponds to the limit of sensitivity.

3.1.2 Indirect method

For small variations of the applied electric field E the first Townsend coefficient $\alpha(E)$ will depend approximately linearly on E and the chamber gain will depend exponentially on E :

$$G(E) \cong \exp(A + B E) \quad (4)$$

If there is a large amount of feedback the total gain will increase over-exponentially, because (eq.(3)) $G_t(E) = G(E)/(1 - \eta G(E))$. The deviation of $G_t(E)$ from an exponential behavior allows an estimation of the feedback level η . This method depends only on the total charge in the avalanche and thereby it can be used also for gases containing He.

The chamber gain was measured at 4 different voltages, spanning about one order of magnitude in gain; the point with the highest gain corresponds to the breakdown limit, as presented in section 5.3. The avalanches were started by X-rays from an ⁵⁵Fe source. The value of η was calculated through a 3 parameter fit (A, B and η) to the curve $G_t(E)$.

The results obtained using this method are also presented in fig.8 (open symbols). It is clear from the dispersion of the points, and the error bars, that the indirect method is less precise than the direct

method, its usefulness coming from the fact that it allows to extend the measurement to gases containing He. Values of η could be obtained by both methods for Ar+TEA gas, and are in qualitative agreement. The higher feedback level measured for Ar+TEA using the indirect method can be attributed to a deviation of $\alpha(E)$ from linearity at low quencher pressures, distorting the curve $G(E)$ and simulating an increase in feedback. The measurements for Ar+TEA and He+TEA by the indirect method suggest a very similar feedback efficiency for both gases, in agreement with the observed breakdown characteristics (see discussion). The points for Ar + 10 Torr CH₄ are in disagreement because the occurrence of edge sparking below 15 Torr for gases containing CH₄ prevented us from reaching the maximum gain at those pressures; we have therefore been unable to reach a value of ηG measurable through the indirect method.

3.2 Ion feedback

There is some probability that the positive ions created in the initial avalanche will extract electrons from the cathode. Most of the secondary electrons will be produced near the end of the ionic signal, when the higher density of ions created near the anode by the initial avalanche reaches the cathode. In that case a second ionic tail should be visible after the one of the initial avalanches. This effect was never observed for any of the gases used, thus suggesting the value of the secondary electron yield to be a small fraction of the primary charge, certainly less than 5%. Since we made observations with an ⁵⁵Fe source producing 220 primary electrons and the final number of ions in the avalanches approached 10⁸ this effect is certainly smaller than $220 \times 0.05 / 10^8 \cong 10^{-7}$ electrons/ion.

In multistep structures, which in principle can achieve very high gain, and particularly in photon counting devices even a small effect of this kind taking place from the second to the first step of amplification can, in principle, produce a sizeable secondary avalanche.

4. Linearity

Linearity of response is an important characteristic of proportional particle detectors. It is well known that in MWPCs the space-charge in the avalanches restricts the single-avalanche linearity for a total charge above $\sim 10^6$ electrons (see for example [12]). This effect manifests itself as a slower growth of $G(E)$ compared to the exponential behavior expected for small variations of E (eq.(4)) and as a non-linearity of the response with the amount of primary charge, sometimes called the semi-proportional regime. Space-charge also affects the count rate capability of these detectors by reducing their gain at high count rates. On the contrary it is known that PPACs have an higher rate capability [4], which makes them very attractive for high rate environments.

Some observations [3] suggest that the response of PPACs doesn't show appreciable deviations from linearity, at least for low pressures and highly ionizing particles. On the other hand a clear space-charge effect is reported in ref.[11] for the amplification of single photoelectrons in low pressure methylal gas, and a space-charge effect distorting the first Townsend coefficient was found in a counter filled with *n*-heptane at 18 Torr [13].

As reported in the previous section an over-exponential behavior of $G(E)$ was observed for some mixtures due to photon feedback, but for mixtures containing a high concentration of quencher the measured values of feedback were compatible with zero. For these mixtures we analyzed the data through a different method, allowing a direct estimation of any deviation of $G(E)$ from exponential behavior, due to space-charge.

Following closely the procedure described in section 3.1.2, for each mixture having negligible feedback we took 4 data points of total charge vs. voltage, spanning one order of magnitude in gain near the breakdown limit. The points taken at highest gain correspond to the breakdown limit presented in section 5.3. An exponential function was fitted through the 3 points at lower gain and extrapolated to a voltage correspondent to the point at highest gain. The difference between the extrapolated value and the measured one provides a quantitative estimation of the deviation of the first Townsend coefficient from linear behavior. It is clear that if some systematic deviation is found, it will constitute an indication of a space charge effect.

In fig.9a several curves of total charge vs. applied field are presented: no individual curve shows a clear deviation from the linear behavior of $\alpha(E)$. For most mixtures there is a good parallelism between curves measured with different values of primary charge, even if the electric field ranges don't overlap. This clearly demonstrates a linear response of the PPAC with varying primary charge density, up to the breakdown limit. The quantitative results (deviation from linearity) are shown in fig.9b. Within our accuracy of about 20% no systematic deviation from linear behavior is observed up to the breakdown limit, either for the α particles or for soft X-rays.

5. Breakdown

The occurrence of breakdown sets the most severe operational limitation for PPACs and in order to improve the operational characteristics of this detectors it would be useful to understand the physics involved in the process. In this work we don't want to discuss minor improvements on the breakdown limit that can be achieved by skillful choice of gas fillings and chamber geometries, but to outline some general trends of the phenomena, illustrative of the underlying physics.

Two main modes of breakdown are identified in the literature (see [14] for a review):

- For reduced values of Pd (total pressure $\times$ gap length) — according to some authors smaller than about 200 Torr·cm in air and analogous values for other gases — breakdown occurs through the "slow breakdown mechanism". This process is originated by feedback through the secondary mechanisms referred in the previous section (photons or ions), the gap breakdown being preceded by many generations of secondary avalanches. There is a qualitative explanation for this type of breakdown (based on refinements to eq.(3)) that predicts the static breakdown potential and maximum gain with some accuracy.
- For higher ranges of Pd (including observations at atmospheric pressure), or for pulsed operation, the breakdown characteristics deviate from those predicted by the slow breakdown model. In particular the breakdown characteristics are largely independent of the cathode material and the formative time-lag of the breakdown pulse is much shorter than required for a many generation process. Some authors [11,15,16] proposed a fast feedback mechanism based on direct gas photoionization and enhanced electron multiplication on an electric field distorted by the

avalanche's own space-charge. This model is known as the "streamer theory", and a lower limit of 5×10^8 electrons per avalanche was experimentally found [11] for the formation of streamers.

From this studies it is not clear which mechanism is effective in our PPAC detectors. Most of the authors studied gases which are different from the mixtures used in our detectors, or they used longer gaps, the gaps were operated in pulsed mode, the pressures reduced, the nature of the electrodes and the methods of avalanche initiation were different, etc. In order to clarify this subject we measured the breakdown characteristics of the PPAC described above, simultaneously with the VUV light emission and the feedback measurements described in the previous section.

5.1 Breakdown in PPACs – qualitative description

We found that both modes of breakdown reported in the literature exist in our PPACs, despite the fact that we are working at a fixed Pd .

5.1.1 Slow breakdown

As described in section 3.1.1 and fig.5, when there is a sufficient secondary photoelectron yield (due to photon feedback) and the gas gain is large enough many successor avalanches are visible. Any further increase in gain will increase the feedback loop efficiency until a self-sustained current appears, corresponding to unity gain in the feedback loop: $\eta G = 1$ in eq.(3). An example is shown in fig.10, for a mixture of Ar+16 Torr CH₄. The current is nevertheless unstable and may decrease or may increase slowly for tens of microseconds until a sharp current rise is observed, followed by a spark, as shown in fig.11.

This form of breakdown is clearly connected with photon feedback to the cathode region or to the cathode itself, breakdown taking place through the "slow mechanism". It will happen whenever the gas gain and the photon feedback efficiency are such that $\eta G \geq 1$, this equation being known as the Townsend breakdown criterion.

The operation of the chamber near the slow breakdown region is very unstable and is not suited for practical operation. The stable regime is separated from the sparking region by a few volts only, making the chamber sensitive to small inhomogeneities in the gap distance. Sparking happens even if a radioactive source is not present: when the source is absent the current grows slowly from a very low level until breakdown, while in the presence of a source the signal starts with the pulse from the initial avalanche growing then until breakdown is reached.

The energy resolution near the slow breakdown limit is modest due to the large contribution to the signal from secondary processes. It is also reasonable to expect a broadening of the avalanche lateral size after a large number of generations, potentially impairing the localization of the avalanches.

5.1.2 Fast breakdown

As described above it is possible to suppress strongly the secondary avalanches by introducing a sufficient amount of quencher in the mixture: the VUV emission is strongly reduced and the VUV absorption in the gas is increased, preventing some radiation to reach the cathode region. In this case breakdown occurs when no successors or very small successors are visible. An example of this process is shown in fig.12. A steep current pulse reaches values well above the normal avalanche level within a delay that is generally smaller than the avalanche transit time. In the following discussion this current pulse will be referred as the pre-breakdown signal, to distinguish it from the final current burst – the spark – known to be the last step of a series of intermediate stages [17].

The operation of the PPAC with gases exhibiting the fast breakdown mode is stable below the critical gain, with good energy resolution and up to large gains. Also the occurrence of breakdown is clearly correlated with the presence of a source.

For X-rays the pre-breakdown signal is generally preceded by a precursor signal, similar to an ordinary avalanche. This feature is also reported in ref.[11] for static fast breakdown in methylal, but it is not visible in other breakdown studies [18,19]. Because the α particles crossed both the 11 mm drift space and the amplifying gap, ionizing the gas uniformly along their path, the avalanche current pulse shape for α s is rectangular, having a width equal to the total drift time of the electrons on the drift space, i.e. a few hundred nanoseconds. Breakdown occurs near the end of the pulse, when the last electrons reach the anode (fig.13). The exact time for breakdown depends slightly on the applied voltage: for higher voltage it happens slightly earlier.

Comparing the behavior of the PPAC near both breakdown modes it is reasonable to admit that all gases used in practice will breakdown through the fast mechanism.

5.2 Transition between slow and fast breakdown modes.

It was mentioned earlier that there is indication in literature that the breakdown mode transition depends on the value of Pd . Since in our case Pd is fixed, it would be interesting to understand the transition between breakdown modes in some detail. This understanding is also of practical interest, since the detector properties change radically near the transition between active breakdown modes.

We measured the breakdown delay for mixtures of Ar and He with TEA, CH_4 and C_2H_6 , as a function of the quencher partial pressure. The avalanches were initiated either by α particles or by 5.9 keV X-rays, as described above. The delay time was measured from the beginning of the proportional signal to a level on the pre-breakdown signal 3 to 5 times higher than the maximum level of the avalanche signal. Fig.14a shows the characteristic breakdown delays for the five gas mixtures studied and both sources of primary charge: open symbols for α s and solid symbols for X-rays.

The existence of two characteristic breakdown delays is clear: for slow breakdown it is typically above 10 μs , while for fast breakdown it lies below 1 μs . As the quencher concentration increases, all mixtures show the appearance of a fast breakdown mode. We will refer to this change of breakdown mode as the transition from the slow to fast breakdown. The quencher concentration at which the transition takes place depends on the gas composition and on the source of primary charge, as summa-

rized in fig.14b (the numerical values near the bars will be discussed below). We would like to note that this results contradict the statement of other authors (mentioned above): in our case Pd was constant ($760 \times 0.4 \text{ cm} \cdot \text{Torr}$) the transition depending on other factors.

The transition always occurs at an higher quencher pressure for ^{55}Fe than for α s. For both Ar+TEA and He+TEA the transition occurs in the same range of partial TEA pressures, suggesting similar levels of feedback. For Ar+CH₄ it was not possible to measure the breakdown delay for X-rays at CH₄ partial pressures below 15 Torr due to edge sparking in the detector, but at this pressure and above the breakdown was of the fast type. For both Ar+CH₄ and Ar+C₂H₆ mixtures a transition for α 's could not be observed above 6 Torr, the minimum concentration we could measure in practice.

As stated above the avalanche current pulse for α s is a few hundred nanoseconds long, corresponding to the total drift time of the electrons on the drift space. Fast breakdown occurs only near the end of the pulse, when the last electrons reach the anode. Coherently with our experimental protocol this drift time is included in the breakdown delay, and for this reason the breakdown delay in the fast breakdown region is generally larger for α s than for X-rays.

5.3 Breakdown limit

There is a high practical interest to know what is the maximum attainable gain for PPACs before breakdown occurs, and how and why it depends on the different operating parameters. In this section we present measurements of the breakdown limit of our PPAC, made simultaneously with the VUV emission and feedback ones.

The breakdown limit was defined as the average total signal charge at an observed sparking rate between 0.1 and 0.5 Hz, for a total counting rate (due to the source) of 100 Hz for the 100 cm² surface. This definition is based on practical reasons: the spark rate is high enough to be easily detected without a long waiting time and not so high to impair the observation of the proportional signals. These sparking rates were adopted for experimental convenience and are certainly too high for the practical operation of any detector. A reduction on the maximum gain should be expected if the sparking criterion is made more strict [20,21]. We found the spark rate to be a steep function of gain, so for all our observations the error on the measured gain limit introduced by the imprecision in the spark rate criterion is below 30% — accurate enough for our purposes.

The gain limit was measured for both 5.9 keV X-rays and α particles, introduced in the detector as described above. For He based gases the energy resolution for X-rays is poor, probably due to the relatively long path of the photoelectron, escaping in part from the drift region. The upper end of the pulse height spectrum is nevertheless sharply defined and we took this region as representative of the chamber gain. Because the PPAC anode mesh is in contact with a dielectric surface (the CaF₂ window) some charge-up effects could in principle be expected, but these were never observed in our set-up.

The experimental results are presented in fig.15. Within a factor 3, a total charge limit of $\sim 10^8$ electrons is found for a 2 orders of magnitude range in quencher pressure, five different gas compositions and primary charges ranging from 220 to 5×10^4 electrons (so the gas gain varies by about two

orders of magnitude). These results strongly suggest a breakdown mechanism dominated by the total amount of charge in the avalanches and largely independent from the gas composition and chamber gain. These results can be compared to those of other authors [11], which measured the breakdown limit under completely different experimental conditions (pressure, gas composition, electrode configuration, primary ionization, etc), and find approximately the same charge limit.

A closer look to fig.15 allows to distinguish a number of features:

- The figure shows both modes of breakdown: slow and fast. Both modes display roughly the same limit on total charge (not on initial charge — fig7), but for mixtures containing TEA there is a tendency to a higher charge limit in slow mode (see discussion).
- Mixtures containing TEA show a fast breakdown limit smaller by a factor ~ 2 compared to mixtures containing simpler hydrocarbons.
- For fast breakdown the charge limit for α s shows a tendency to be slightly higher than for X-rays. This effect may be due to the pointlike concentration the primary charge from X-rays compared to the extended track left by the α particles.

Since we observed a dependency of the breakdown limit with the angle of the α particles, all measurements here described were done with tracks almost perpendicular to the electrodes. As stated above, the breakdown for α s occurs when the last electrons from the track reach the anode. If the tracks are perpendicular to the gap all electrons will fall in the same avalanche but if the tracks are inclined there will be an extended avalanche, following the projection of the track on the anode surface. In that case the single avalanche charge limit doesn't apply and the total charge can be higher.

5.4 Multistep avalanche chamber

The multistep avalanche chamber (MSAC) as been introduced by Charpak and Sauli [22], in order to reduce photon feedback and provide gateability. It would be interesting to see if the fast breakdown limit in this kind of detector is higher than in the single step configuration.

We made two brief tests, in order to get some indication about this effect. One of the tests was made using the installation described above, where we used the 11 mm conversion gap as a first stage of amplification. After optimization of the gain configuration in both stages, the gain for α particles was measured, for several Ar+TEA mixtures. In the best case we found an improvement on the breakdown limit by no more than a factor 2.

A second test was made using the device described in ref.[5]. It is a double step chamber where α particles are introduced, almost parallel to the plates, in a conversion gap that precedes two amplification gaps. The primary charge yield is estimated to be 2×10^5 electrons, with a pathlength of ~ 15 cm in a He+TEA gas. The sparking always occurs in the last gap, which was designed to withstand a high sparking rate without inconvenience, and is always localized near the end-of-path of the α particle where a larger primary charge density is deposited. The total count rate was around 20 Hz.

Two measurements were done; unitary gain in the first gap and $\sim 10^4$ in the second gap, corresponding to a single step operation; gain $\sim 10^3$ in the first gap and ~ 10 in the second gap for multistep operation. The results, presented in fig.16, show only a small difference between the two configurations: the onset of sparking appearing at $\sim 1.5 \times 10^9$ electrons. Although the orientation of the α tracks was not the same as for the measurements described above (in particular the breakdown limit of 10^8 electrons doesn't apply) the comparison between single and double-step operation is still valid.

Both measurements indicate that the multistep structure may increase the fast breakdown limit by a factor 2-3 at most. Similar observations were reported [21,23] for double and three-step PPACs.

6. The first Townsend coefficient and the light emission coefficient.

In the framework of the streamer model the behavior of the first Townsend coefficient and the VUV light emission with electric field should play an important role. In this section we try to find a phenomenological law to describe how these quantities change with the electric field, which will be used later to explain the observations concerning breakdown. Analytical approximations are also useful because they provide a guide in estimating the influence of changes in the external parameters on the chamber's behavior, predict the operating voltages for given gain, etc.

The total charge in the avalanche was measured as a function of the applied voltage for several gas mixtures, using both a 5.9 keV X-ray source and a 5.5 MeV α source as described above. The combination of both sources allowed to span the gain range from 100 to 5×10^5 . The α coefficient was calculated by inversion of the formula (2).

For many gases, including the noble gases and some commonly used hydrocarbons [11,24], a simple approximation exists for the first Townsend coefficient α as a function of total pressure P and electric field E :

$$\frac{\alpha}{P} = A e^{-B \frac{P}{E}}$$

Based on our measurements, we looked for a similar law describing binary mixtures of a noble gas and an hydrocarbon.

For the mixtures studied (Ar and He + CH₄, C₂H₆ and TEA) we plotted, in fig.17, $\log(\alpha/p)$ vs. p^k/E . The experimental points cluster along a straight line, suggesting an analytical approximation of the form.

$$\frac{\alpha}{p} = A e^{-B \frac{p^k}{E}} \quad (5)$$

Where now p is the quencher concentration. The additional dimensionless parameter k depends on both constituents of the gas. The fitted values of A , B and k along with the measured ranges of α , E and p are resumed in the following table:

Table 1: Parameters in eq.(5) for several mixtures.

Mixture	A (cm·Torr) ⁻¹	B kV/cm·Torr ^{1/2}	k	α cm ⁻¹	Validity p Torr	range E kV/cm
Ar+TEA	134	4.42	0.65	13-33	1-40	2.1-9.8
He+TEA	96.7	2.97	0.65	18-32	1-30	2.1-6.3
Ar+CH ₄	16.0	5.91	0.45	15-33	10-80	7.8-12
He+CH ₄	16.5	1.10	0.70	20-34	8-80	2.5-5.5
Ar+C ₂ H ₆	28.4	3.75	0.55	14-35	6-60	4.1-9.0

The parameters A and B were calculated by fitting a straight line to the experimental points presented in fig.17 and the value of k is the one that minimizes the fit errors. The values presented for A and B are exact within 1% and the uncertainty in k is about 3%. The fact that eq.(5) describes the data for mixtures containing either CH₄ or TEA, despite the widely different energy levels of these gases, allows us to expect the law to be valid also for other quenchers with intermediate energy levels, as confirmed by the measurements with C₂H₆.

The results of the VUV emission measurements described in ref.[10] (in the range 120 to 170 nm) can be used for the interpretation of photon feedback and breakdown phenomena. For this reason an extended series of measurements of the VUV emission, using the same methods described in that ref., were done in order to find a link between the first Townsend coefficient and the VUV light emission. From the physical point of view we can expect the ionization and excitation phenomena to obey similar laws, since they are both the result of direct electron impact. A light emission coefficient (δ) similar to α can be defined by considering the equations describing the growth of light and charge in the gap during the avalanche:

$$\frac{dn_e}{dx} = \alpha \cdot n_e$$

$$\frac{dn_l}{dx} = \delta \cdot n_e$$

Where $n_e(x)$ ($n_l(x)$) is the number of electrons (photons) created up to the moment the cloud reaches a distance x in the gap and δ is the number of photons emitted per electron per unit path length, having the same dimensions as α . The equations can be integrated yielding:

$$n_e(x) = n_{e0} e^{\alpha x}$$

$$n_l(x) = \frac{\delta}{\alpha} (n_e(x) - n_{e0})$$

The measured VUV light emission yield (photons/electron) is in fact $n_l(d)/n_e(d) \cong \delta/\alpha$, so δ can be calculated by multiplying the measured integral values of the light emission by α .

The experimental points¹ were plotted in fig.18, following the same presentation as for fig.17. For He + TEA, He + CH₄ and Ar + TEA the points tend to align along a straight line and we can consider the approximation (5) verified. For Ar + CH₄ there is a clear violation of this approximation: the different clusters of points correspond to different partial pressures of CH₄ and, unlike what was observed for the other gases, δ doesn't grow with the electric field. For Ar + C₂H₆ the data are sparse, but a tendency to violate eq.(5) can also be perceived.

The following table shows the A, B and k parameters in the formula

$$\frac{\delta}{p} = A e^{-B \frac{p^k}{E}} \quad (6)$$

providing δ in analogy with expression (5).

Table 2: Parameters in eq.(6) for δ/p of several mixtures (from fig.18).

Mixture	A (cm·Torr) ⁻¹	B kV/cm·Torr ^{1/k}	k(±0.08)
Ar+TEA	2.16	7.92	0.75
He+TEA	0.38	8.23	0.6
Ar+CH ₄	4.24×10 ⁻²	5.76	0.6
He+CH ₄	4.89×10 ⁻³	1.11	0.8
Ar+C ₂ H ₆	3.22	9.31	0.6

7. Discussion

7.1 Feedback and breakdown

The main conclusion from the feedback measurements is that the photon feedback sharply decreases with the quencher partial pressure. This behavior qualitatively agrees with the behavior of the VUV emission from avalanches, measured for the same gases [10].

As described above, two modes of breakdown were identified in PPACs: a slow breakdown mode and a fast breakdown mode. According to our interpretation (supported on the timing characteristics of the observed signals) slow breakdown is connected with photon feedback from the cathode itself, or

¹ Those points measured using α particles and having total charge between 10⁷ and 5×10⁷ electrons were also included in ref.[10]. The gain ranges presented here are more extended.

from the gas in the vicinity of the cathode. Those photoelectrons created inside the amplifying gap will experience a much reduced gain and cannot contribute noticeably to photon feedback. The onset of slow breakdown is thought to be described by the Townsend criterion: $\eta G \geq 1$. Since the photon feedback efficiency η can be decreased below 10^{-6} (see fig.8) by the introduction of a sufficient amount of quencher it could be expected that relatively high gains of 10^6 or larger could be achieved in one step PPACs. In reality, whenever the total charge on the initial avalanche exceeds 10^8 electrons (fig.15), breakdown will happen through the fast mechanism, which seems to be independent of the photon feedback level.

For a given gas mixture the active breakdown mode will depend on which criterion is met at lowest gain:

$$\begin{aligned} \eta G &> 1 && \text{Slow breakdown} \\ N_0 G &> 10^8 && \text{Fast breakdown} \end{aligned}$$

The gain can be eliminated dividing equations, yielding a single quantity defining which breakdown mode occurs in a given gas:

$$B_m = \eta 10^8 / N_0$$

and

$$\text{Slow Breakdown} \quad 1 < B_m < \infty \quad \text{Fast Breakdown} \quad (7)$$

For instance, if the primary charge is created by 5.9 keV X-rays depositing 220 electrons then the fast breakdown criterion will be reached at $G = 5 \times 10^5$, the maximum possible gain for those particles. If $\eta > 2 \times 10^{-6}$ then the slow breakdown criterion will be met at a gain lower than 5×10^5 and the gap will breakdown through the slow mode.

The quencher pressure at which the transition between breakdown modes occurs (p_t) for 5.9 Kev X-rays will be such that $\eta \sim 2 \times 10^{-6}$ ($2 \times 10^{-6} \cdot 10^8 / 220 = 0.9$). A similar calculation performed for α particles yields $\eta \sim 5 \times 10^{-4}$ for Ar-based gases and $\eta \sim 5 \times 10^{-5}$ for He-based gases. On the other hand, since the fast breakdown limit is only known within a factor of 2, this criterion is affected by about the same error.

In fig.14b the value of B_m is written near the extremes of the mode transition zones p_t , whenever there is data available for η in those regions (see fig.8). The relatively large errors in the measurement of η gives to this factor an indicative character, but nevertheless for all cases the value of B_m approximately agrees with the observed breakdown mode; thus confirming the validity of eq.(7).

Note that p_t is the same for Ar+TEA and He+TEA gases, in agreement with the very similar behavior observed for η in these gases. Also, since η grows with decreasing quencher concentration, eq.(7) predicts that for a given gas p_t will decrease with increasing primary charge, which is the case for all gases studied.

We can say that the combination of the Townsend criterion with a constant fast breakdown limit allows to describe the transition between active breakdown modes in PPACs.

7.2 Breakdown limit

As already stated the chamber operation near the slow breakdown conditions is very unstable and rather useless in practice. For this reason we will concentrate on the fast breakdown mode properties.

The fast development of the pre-breakdown signal rules out any contribution from secondary electrons created in the cathode region and reamplified in the gap, since the process develops in a time scale shorter than the avalanche gap-crossing time and lacks a "generations" structure as in the case of slow breakdown. The feedback process actually responsible for the current growth should be active near the anode and the feedback loop must span a short length in space, allowing a fast regeneration.

The considerations above describe typical features of a "streamer" mediated breakdown as described by other authors [11,15,16,25]. According to this model the streamer is a self-amplified avalanche, growing due to a fast feedback mechanism based on direct gas photoionization by the avalanche's own emission (self-photoionization) and enhanced electron multiplication on an electric field distorted by the avalanche's space-charge. The field enhancement by the avalanche's space charge is regarded as essential for the development of the process, so for an avalanche to grow into a streamer a critical space-charge level must be reached. The critical space-charge must be such that the field distortion becomes non-negligible compared to the applied field. In this picture the streamer will necessarily follow an initiating avalanche, explaining the good correlation between the presence of a source and sparking.

This model of the fast breakdown mechanism allows an interpretation of the fact that for α particles breakdown always occurs near the end of a time-extended avalanche, but at the same total charge as for a concentrated avalanche: the accumulation of positive ions in the gap during the development of a time-extended avalanche distorts the electric field proportionally to the total amount of charge collected, so only when the last electrons reach the gap the total charge distortion may become comparable to the applied field and a streamer can develop. The gap acts like keeping for some time a "memory" of the avalanches previously occurred, the charges of individual avalanches adding up during the "memory time". This "memory effect" will be used below to explain some other properties of PPACs.

There is nevertheless a difficulty in the interpretation of the experimental results through a photon mediated process. We studied gases having widely different properties concerning emission and absorption spectra, photosensitive thresholds, etc. It would be reasonable to expect wide variations in the efficiency of a process based on photon emission and absorption, resulting in variable breakdown limits. On the contrary, the breakdown limit remains constant over a wide variety of circumstances, suggesting a universal mechanism for fast breakdown. In the next section we qualitatively outline a number of effects that allow an interpretation of the breakdown limit independently of the self-photoionization characteristics of the gas.

7.2.1 Space-charge related gain distortion.

When an avalanche proceeds in the amplifying gap three main regions of field distortion can be calculated (fig.19 reproduced from [26]). The part of the avalanche in front of its maximum electron density will experience an increased electric field due to the repulsion by the electrons in the avalanche core. Just before the avalanche maximum the field will be decreased due to repulsion from the electrons in the avalanche core, now in the opposite direction, and attraction from the cloud of ions remaining in the avalanche's tail. Further into the cathode side the main contribution will be due to the attraction from the ion cloud, whose density increases towards the anode, resulting on an increased field.

According to ref.[25], if the field distortion is sufficiently high, the enhanced electron multiplication on the front part of the avalanche will generate an anode-directed streamer and if some degree of gas self-photoionization exists the reamplification of those photoelectrons through the rear part of the avalanche will generate a cathode-directed streamer. The same author calculates a limit of $\alpha d \sim 20$, that is $N_e \sim 5 \times 10^8$, for the avalanche size that equals the space charge field to the applied field, in agreement with the experimental results of other authors [11]. We should note that a similar limit is found by Meek and Raether [16,11] using a simple qualitative model, and also by numerical models developed by several authors (see for example [26,27]). The calculated limit referred above concerns breakdown in longer gaps than in our case, but a linear dependency between the gap length and the breakdown limit is also reported in ref.[11], bringing the limit into agreement with our result of $\sim 10^8$ electrons. This increase of the breakdown limit with d may explain the slightly higher breakdown limit observed in MSACs.

If we consider now the measured curves for the first Townsend coefficient, described by eq.(5), and we choose a particular value of p , we can draw the curve $\alpha(E)$ for any particular gas composition. From the knowledge of α the behavior of the gain as a function of E is easily calculated. In fig.20 we computed the gain in a section of the gap 1 mm long as a function of the local electric field, for a quencher partial pressure of 20 Torr and several gas mixtures. This quencher concentration corresponds to a commonly used gas composition, allowing a stable chamber operation. The normal operation point (gain of 20 in 1 mm corresponding to a gain of around 10^5 on a 4 mm gap) is represented by a straight line which intercepts the curves at the operating field for each gas; if we take the curve for Ar + TEA gas, for instance, the operating field will be 6.5 kV/cm, in the 4 mm gap..

The points superimposed over the lines were not directly measured, but they were converted to 20 Torr from the actually measured ones, presented in fig.17. Their only purpose is to mark the ranges actually measured from the extrapolated region of the curves. The conversion was done using similarity laws that respect eq.(5): $p_1^k/E_1 = p_2^k/E_2$ and $\alpha_1/p_1 = \alpha_2/p_2$

If an avalanche's space-charge distorts the local electric field by 3 kV/cm in the Ar + TEA gas, for instance, the local gain changes from the operating value of 20 in 1 mm to about 5×10^5 . At such high gains a streamer would easily develop.

The VUV light emission coefficient (see fig.18) is strongly dependent on the electric field. In Ar + TEA, for instance, a factor 2 increase in E corresponds to ~ 2 orders of magnitude increase in the VUV light emission. If a similar behavior is assumed to apply to the emission bands responsible for self-photoionization in any gas then this effect along with the gain enhancement makes plausible the universality of the breakdown limit. Since the gain on the fast feedback loop (photoemission $\times$ pho-

to absorption $\times$ local gain) can be increased by many orders of magnitude by relatively small variations in field, any *a priori* differences between gases will be levelled out by relatively small variations in the avalanche size, once the avalanche space-charge field distortion becomes comparable to the applied field. The breakdown limit corresponds then to an avalanche charge density such that its space-charge field distortion is comparable to the applied field, so it can influence the local α and δ .

Fig.20 also suggests that gases containing TEA are more sensitive to variations of the electric field than gases containing the simpler hydrocarbons. It is interesting to note the existence of a difference by a factor ~ 2 between the breakdown limits of these classes of gases, as can be seen in fig.15.

The space-charge field distortion depends on the charge density of the avalanche, so the breakdown limit should be sensible to any factors affecting the avalanche's volume, like electron diffusion in the gas and focusing magnetic fields. In fact both effects were observed experimentally [20].

Not all observed qualitative details of the fast breakdown process are explained by the streamer model described above. For example, it is not clear if a streamer process is compatible with the observed existence of a precursor to the pre-breakdown signal. It would seem that when the avalanche reaches a sufficient size the gain enhancement will make the current to grow steadily. The current reduction between the precursor and the streamer doesn't fit well into this picture. A very qualitative interpretation exists in the literature [11] and to give a quantitative expression to the fast breakdown model a numerical study of avalanche amplification and streamer formation under gas self-ionization conditions is in progress and will be published later [28].

7.3 Source rate and breakdown limit

In this section we discuss results from other authors concerning the breakdown properties of PPACs and attempt to explain them on the realm of the space-charge model.

7.3.1 Results from other authors

An exponential decrease of the maximum operating voltage of a PPAC at increasing source rate has been observed (see fig.21 reproduced from ref.[29]). Since the gain depends exponentially on the applied electric field one can infer a dependence between the maximum attainable gain and the source rate on the form of an inverse power law. These results along with other experimental data on sparking are further developed in ref.[20].

Another interesting effect is the dependence of the maximum gain on the collimator aperture for fixed primary charge per unit surface. The authors suggest a space charge effect based on the average field from the column of positive ions constantly present in the gap. There is a difficulty in this approach, acknowledged by the authors of ref.[20]: the effect is visible at rates as low as 2 kHz (0.5 mm diameter collimator at 10^4 counts/mm²·s); since the transit time for ions is at most 50 μ s, at the quoted rate there are no ions in the gap for 90% of the time!

An increase of the maximum gain attainable was observed when the transfer gap is gated, i.e. letting the preamplified ionization electrons into the second gap only in coincidence with a short electronic pulse applied to a gating electrode [23]. The effect persisted even if a large fraction of the signals were allowed into the second gap. Apparently the increase in the maximum gain is not related with the total counting rate in the second gap but simply with the existence of a gate. It should be realized that the gate (30 ns long) remains closed for most of the time, even for large transfer fractions. According to the authors the gating would eliminate the feedback from positive ions, thus increasing the maximum gain.

All the preceding effects are only apparent for relatively high counting rates, from 1 up to 100 kHz.

Our results suggest that any amplifying gap in good working conditions will breakdown through the fast mechanism, the operation being too unstable otherwise. Also in case the sparking is due to ion feedback to the first stage, the spark would follow the avalanche after a delay of a few hundred microseconds; the drift time of the positive ions from the last anode to the first gap cathode at a distance of 2.5 cm. Such feature should be easily recognizable. On the other hand if breakdown is not related to feedback, but instead to the average ionic field as suggested to explain the collimator effect for instance, the gating effect cannot be explained.

7.3.2 Spark rate and probability

The process leading to breakdown is stochastic: the avalanches generate sparks according to a certain probability law, so for a fixed breakdown probability per avalanche the breakdown should be more frequent for higher source rates. If the breakdown limit is defined at a constant spark rate then a reduction in gain will be necessary to compensate the increased total spark probability due to an increased source rate. Following these lines we would like to suggest a mechanism that explains the observations described above and agrees also with our results.

According to our interpretation the gap breakdown occurs when a certain critical amount of charge is reached in an avalanche, that we explain as a space-charge induced field distortion comparable to the applied field. There should be nevertheless a memory effect due to the slowly moving positive ions remaining in the gap for a few μ s. A second avalanche following closely the first one will be affected by this ion cloud, the respective space charges adding up. Our observation that for α particles breakdown occurs at the end of the pulse (few hundred ns long), when the last electrons reach the anode (see fig.13) supports this hypothesis.

If a chamber is set near the critical charge limit for a given amount of primary charge and a second avalanche occurs in the same position within the memory time, the breakdown threshold will be crossed and a spark will develop. This memory time being at least of 1 μ s, as suggested by the breakdown observations with α particles. In order to interpret the measured curves of source rate vs. maximum field and the collimator aperture effect a semi-quantitative approach is required. In the following calculation a fixed amount of primary charge is assumed: 300 electrons from 8.9 keV X-rays in the case of ref.[29]. Based on our hypothesis the sparking rate will depend on the probability of having two avalanches close to each other in space and time, on the total source rate and on the probability that a double avalanche will produce a spark, this probability being a function of the chamber's gain.

Assuming a Poisson distribution for the emission of X-rays, the probability of having exactly n photons emitted within any time interval t is

$$P_t(n, Rt) = \frac{e^{-Rt} (Rt)^n}{n!}$$

where R is the average source rate and Rt is the average number of photons emitted in the interval t . If the time interval t is counted after the emission of a photon the probability we are interested at is $P_t(n=1, Rt)$, t being the memory time. We are considering $R < 10^5 \text{ s}^{-1}$ and $t < 10^{-6} \text{ s}$, so $Rt < 0.1$. In this conditions $P_t(n > 1)$ is negligible compared with $P_t(n = 1)$ and the expression above reduces to

$$P_t(1, Rt) \cong Rt$$

If we define σ as the surface of a disc centered on the avalanche's core where the superposition effect is possible (the avalanche "cross section"), the probability of superposition is σ/a . The collimator aperture (surface) is represented by a . For the probability that a double avalanche will produce a spark we will assume

$$P_s(G) \propto G^m$$

the value of m (positive) being irrelevant for the discussion. This hypothesis is based on a fit to experimental results presented in ref.[20]. The total spark rate will be

$$R_s = \frac{\sigma}{a} \cdot Rt \cdot G^m \cdot R$$

or:

$$\frac{R}{a} = \sqrt{\frac{R_s}{a\sigma}} G^{-m/2}$$

Since it is know that for high gains the gain is exponentially dependent on E we will use eq.(4)

$$\frac{R}{a} = \sqrt{\frac{R_s}{a\sigma}} e^{-\frac{m}{2}(A+B \cdot E)} \quad (8)$$

or

$$\log\left(\frac{R}{a}\right) = \frac{1}{2}\log\left(\frac{R_s}{a\sigma}\right) - \frac{m}{2}(A+B \cdot E)$$

The dependence of $\log(R/a)$ on E , for fixed spark rate criterion ($R_s = \text{const}$) and collimator aperture (a), is linear with a negative slope, exactly as displayed in fig.21. On what concerns the collimator aperture effect we should note that the right hand side of eq.(8) depends on $1/\sqrt{a}$, that is, on $1/d$, d being the collimator diameter. Now, if the experimental points are plotted like $\log(Rd/a)$ vs. E all dependence on d should disappear and curves taken at different d should overlap. On fig.22 we reploted the experimental points of fig.21 with the vertical coordinate multiplied by the collimator diameter: the points cluster around a straight line as predicted by our model.

Note that if there was no time correlation between events then the spark rate should be proportional to R and not to R^2 , and the collimator effect cannot be explained since the points for different collimator diameters would not superpose. It is clear that for reduced source rates any avalanche pile-up would be negligible and a different interpretation of R_s vs. G should apply. The reason why $P_s(G) \propto G^m$ is also unclear.

The superposition effect can also explain the increase in gain observed when the multistep chamber is gated. If the signal sensed in first gap is used to trigger the gate then avalanches close enough in time will not be resolved by the trigger system, counting as single one. The short, 30 ns wide gate, will open to the first electron cloud but it will close to the second one, chopping off the excess charge, eliminating a possible superposition and avoiding the spark.

Therefore, our qualitative model based on the crucial role of critical space-charge explains not only our results, but also those of other authors.

7.4 Advantages of the multistep avalanche chamber.

From the considerations and results presented in the preceding sections, it would seem there is no advantage, from the point of view of gain, to use a ungated MSAC. Indeed the results presented in 5.4) support this point of view. Of course the possibilities of gating, self-triggering and the built-in time delay are valuable by themselves, but there are some other benefits in the MSAC which in a real environment may be crucial for the correct operation of the detector. In the following lines we list several factors that help to make the MSAC superior over a single-step structure.

Any environment is radioactively noisy and most forms of radioactivity are able to produce dense clusters of primary charge. Of course, near an high energy particle beam the background radiation can only be more severe. If the chamber operating point is set near its breakdown limit for a given class of radiation to detect, single photoelectrons for instance, it is likely that any highly ionizing background event will produce a spark. The gated MSAC divides its gain over several amplification steps, each of them operating at a low gain and individually quite insensitive to the background radiation; upon an external trigger the chamber gates open and let the full amplification to be applied only to the selected events, rejecting the background radiation.

As observed for the PPAC, it is likely that photon feedback doesn't contribute decisively to the breakdown limit of the MSAC, but it may degrade other desirable characteristics, like the localization accuracy. Two features contribute to the suppression of feedback in MSAC: the large distance between the high-gain region that precedes the first gap and the final gap where the full gain is achieved, and the gate that suppresses any after-pulses. The main form of photon feedback which cannot be avoided is the feedback from the first gap to the conversion space that normally precedes it. Even for this case the low gain operation of this gap makes the effect less important, compared to a single-step structure. It is clear that the ion feedback, if any exists, will be also strongly suppressed by the gate and by the small transfer efficiency from the last gap into the transfer gap, due to the configuration of the electric fields.

Mechanical defects on the gap edges, spacers and meshes may induce localized sparking and reduce the maximum chamber gain. These defects can normally be corrected, but they are an extra

source of trouble for the construction of large detectors. The multistep structure, operating at a lower gain per gap, is more tolerant to these defects.

An important requirement for any detector is the homogeneity of response over the full active area. In PPACs the main disturbing factor is the lack of parallelism of the amplifying gap, limited by the mechanical construction and by the deflection of the gap meshes under electrostatic attraction. If we represent the chamber gain by formula (4) it is easy to see that $\delta G = A \cdot G \cdot \delta d$, so a gap working at reduced gain will be much less sensitive to mechanical tolerances in the gap spacing.

It is clear that all the improvements provided by the MSAC result in a more reliable and flexible detector than a single-step configuration. Some authors [21] recommend the use of three amplification steps for optimally stable operation in a large surface photon-counting MSAC detector, the fundamental limitation remaining the breakdown limit for the accepted events.

8. Conclusions

As a result of this work we clarified several characteristics of PPACs.

The photon feedback in PPACs was measured for several commonly used gases. It was found to depend on the nature of the quencher and noble gas and to decrease very fast when increasing the concentration of quencher. The photon feedback efficiency can certainly be reduced below 10^{-6} photoelectrons/electron in the avalanche (our limit of experimental accuracy). No ion feedback was observed, being certainly below 10^{-7} electrons/ion. The negligible feedback level at sufficiently large quencher concentrations allows to reach a high gain (at least 5×10^5) even in a single step PPAC, without any secondary avalanches. This observation may extend the field of application of single gap PPACs.

The PPAC shows very small deviation from the exponential growth of gain with electric field, up to a gain close to breakdown, indicating a good linearity of response with respect to primary ionization up to the maximum gain.

Two types of breakdown were identified, distinguished experimentally by the time delay between the initial avalanche and the occurrence of spark (breakdown delay). Slow breakdown occurs in situations of strong photon feedback from the cathode region, and with a delay of 10 μ s or higher. The operation of the detector near this breakdown regime very unstable and not suitable for practical operation. If feedback is negligible then a different, fast breakdown mode, takes place. In this mode the spark follows the initial avalanche after a few tens of nanoseconds. The operation of the PPAC near this mode of breakdown is stable up to large gains.

We observed that fast breakdown occurs at a constant charge limit of $\sim 10^8$ electrons, for quencher concentrations within 2 orders of magnitude, five different gas compositions and primary charges from 220 to 5×10^4 electrons (so the gas gain varies by about two orders of magnitude). These results strongly suggest a fast breakdown mechanism dominated by the total amount of charge in the avalanches and largely independent from the gas composition and chamber gain.

The observations described above can be summarized in a single breakdown mode transition criterion:

$$\text{Slow Breakdown} \quad 1 < \eta \cdot 10^8 / N_0 < 1 \quad \text{Fast Breakdown}$$

The transition point depends on the gas composition, in particular on the quencher partial pressure on which depends the photon feedback efficiency (η). This criterion is well supported by the experimental data.

The first Townsend coefficient was found to be described by an exponential expression as a function of the quencher partial pressure and electric field, for several gas mixtures, quencher pressures and field ranges corresponding to normal operation. The VUV light emission coefficient (from ref.[10]) also follows a similar law for some mixtures. The fact that this expression describes the behavior of mixtures containing either CH_4 or TEA, despite their very different energy levels, allows us to expect the law to be valid also for other quenchers with intermediate energy levels. This was confirmed by measurements with C_2H_6 .

The previous result suggests a strong increase in gain and VUV light yield as the electric field increases, allowing to justify the strangely constant fast breakdown limit on the basis of an avalanche space-charge induced electric field distortion. Based in this model we have explained the reasons of the rate effect in the breakdown limit of PPACs and the beneficial effects of gating in MSACs for high-rate operation at high-gain. Gases having slowly growing first Townsend coefficient and light emission coefficient may show promise as less prone to sparking, and will be investigated in the future.

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Figure captions

- Figure 1: Schematic view of the experimental setup.
- Figure 2: Electrical circuit used for the measurements.
- Figure 3: A test pulse having a 3 ns rise-time is superposed to an avalanche current signal. The test pulse rise time is shorter than the avalanche signal slopes, resulting on an avalanche signal shape relatively unaffected by the readout electronics. Some small oscillations follow the impulses, originating from the signal reflection on the chamber electrode's edges.
- Figure 4: Avalanche in Ar + TEA gas. The TEA concentration (30 Torr) was chosen such that no feedback effects are visible.
- Figure 5: Avalanche followed by a few secondary avalanche generations. The gas - Ar + 8Torr CH₄ - is not photosensitive above 100nm, so it is plausible to assume that the photoelectrons were mostly generated by photoelectric effect in the cathode mesh. The regularity in time of the successors and their good temporal definition support this hypothesis. The delay between peaks agrees with a drift speed of $4\text{mm}/100\text{ns} = 4\text{ cm}/\mu\text{s}$. After the third avalanche there is a blurring of the peaks, which may be due to the arrival of photoelectrons extracted from the upper (conversion gap) mesh.
- Figure 6: avalanche with feedback in Ar + 6 Torr of TEA. The secondary peaks are diffuse. Because the gas is photosensitive the most sensitive region for photoconversion should be the conversion region just after the gap's cathode. The photons emitted by the initial avalanche will then be converted at different distances from the amplifying gap, dispersing the temporal definition of the secondary avalanches.
- Figure 7: Ratio of the charge in the 1st avalanche to total charge in the signal vs. quencher concentration, for Ar+TEA and Ar+CH₄. For reduced concentrations of quencher the first avalanche contributes only by a fraction of the total charge, due to a large amount of feedback.

- Figure 8: Measurement of the feedback efficiency (η). Closed symbols for direct method, open symbols for indirect method.
- Figure 9: a) Total charge vs. Applied field for two different primary charge surface densities (as projected to the anode). b) Estimated deviation from linearity of response.
- Figure 10: Feedback efficiency $\simeq 1$. An almost constant current (aftercurrent) follows the initial avalanche, after a few well defined successors. The avalanches were initiated by 5.9 keV X-rays.
- Figure 11: For some pulses the aftercurrent decreases and in other cases it diverges producing a spark (slow breakdown). The VUV emission, detected through the methods described in ref.[10], shows approximately the same behavior.
- Figure 12: Fast breakdown with an X-ray source, featuring precursors. The very fast current growth after the precursor signal excludes any contribution to this process from feedback photoelectrons originated near the cathode region.
- Figure 13: Fast breakdown with α particles. Breakdown occurs mainly near the end of the electron component of the signal.
- Figure 14: a) Breakdown delay vs. quencher pressure for several mixtures and two different sources of primary charge. The two modes of breakdown appear clearly separated. The variation of the measured values is $\sim 50\%$ of the average; the corresponding error bars were not plotted to avoid obscuring the picture. b) The quencher concentration at which the transition takes place (p_t) depends on the gas composition and on the source of primary charge. The value of the breakdown mode criterion (eq.(7)) is written near the extremes of the mode transition zones whenever there is data available for η (fig.8) in those regions. In some cases the value taken for η was linearly interpolated between two experimental points (fig.8), and for Ar+TEA at 4 Torr it was extrapolated (+).
- Figure 15: Breakdown limit (average signal charge) vs. quencher pressure for several mixtures and two different sources of primary charge. The points marked with smaller symbols correspond to slow breakdown.
- Figure 16: Spark probability vs. Total charge in a multistep avalanche chamber for single-step and double-step configurations. Only a small difference in collected charge for a given spark probability is observed between these modes.
- Figure 17: α/p vs. p^k/E . The experimental points are in good agreement with eq.(5) (see table 1).
- Figure 18: δ/p vs. p^k/E . For some gases the data is in agreement with eq.(6) (see table 2).
- Figure 19: Variation of electron density, electric field and light output along the axis of a single avalanche for various times [26]. The units for the first graph are given in the table.
- Figure 20: Gain in a section of the gap 1 mm long as a function of the local electric field, for a quencher partial pressure of 20 Torr and several gas mixtures, computed from eq.(5).
- Figure 21: Dependency between the primary charge deposition density and the maximum working voltage in a PPAC [20]. A dependency on the collimator diameter is also evidenced.

- Figure 22: Points from fig.21 replotted with vertical scale multiplied by the collimator diameter. The dependency in d is compensated demonstrating the validity of the pile-up model (see text).

Fig.1

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