The Fundamental Limitations of High-Rate Gaseous Detectors

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Abstract

Future high-luminosity experiments make serious demands on detector technologies and have prompted a "chain" of inventions of new high-rate gaseous detectors: Microstrip Gas Counters (MSGC's), Microgap Chambers (MGC's), Compteur A Trou (CAT's), Micromesh Gas Structure (MICROMEGAS), and Gas Electron Multipliers (GEM's).

We report results from a systematic study of breakdown mechanisms in these and other gaseous detectors recently chosen or considered as candidates for high-luminosity experiments. It was found that, for all the detectors tested, the maximum achievable gain before breakdown appeared, dropped dramatically with rate, sometimes inversely proportional to it. Further, in the presence of alpha particles, typical of the backgrounds in high-energy experiments, additional gain drops of 1–2 orders of magnitude were observed for some detectors. We discovered that the breakdown in these detectors was through a previously unknown mechanism for which we give a qualitative explanation. We also present possible ways of increasing the value of the maximum achievable detector gain at high rates and have verified these experimentally.

I. INTRODUCTION

Addressing the needs of planned high-luminosity experiments has prompted a series of inventions of various types of novel high-rate gaseous detectors: MSGC's [1], MGC's [2], CAT's [3], MICROMEGAS [4], and GEM's [5]. Many of these have been accompanied by assertions that they would satisfy all the requirements for high-luminosity operation and, due to these initial claims and the fact that extremely tight time scales were involved, these detectors were almost immediately adopted for large experiments at the European Laboratory for Particle Physics (CERN) and elsewhere.

We have discovered recently, however, that the maximum achievable gain in all gaseous detectors drops dramatically with rate, in most cases inversely proportional to it [6]. Further, in the presence of alpha particles, typical of the backgrounds in high-energy experiments, additional gain drops of 1–2 orders of magnitude were observed. This effect renders many devices marginal in high-rate applications and hence their characteristics should be scrutinized closely before failures occur in high-cost experiments now under construction.

The aim of this work is to understand the physical mechanisms involved in high-rate breakdowns and to identify possible ways of optimizing a detector's gain/rate characteristics.

II. EXPERIMENTAL SETUP

Our setup has been described in detail elsewhere [7], [8]. Rate-induced breakdown was studied in micropattern detectors that included: diamond-coated MSGC's with 0.5- and 1-mm pitch, the CAT detector, and MICROMEGAS. Their designs were fully described in references [7]–[10]. We also studied the above detectors with preamplification structures: GEM's or Parallel Plate Avalanche Chambers (PPAC's) (see reference [11] for more details). These studies were done in various Ar- and Xe-based mixtures at 1 atm pressure.

As a source of ionization, an x-ray tube was used (with a line around 6 keV) which could provide up to 10^7–10^8 counts/s/mm^2 in the detector. In some measurements, alpha particles (5.5 MeV) were used, collimated perpendicular to the detector's surface.

In contrast to other previous studies, we concentrated here on a detailed study of prebreakdown and postbreakdown phenomena. For this purpose a fast-current amplifier was used to enable observations of current variations in each detector with a ~20-ns resolution time. Signals from the amplifiers were recorded with a storage scope. One could monitor the phenomena between 20 ns and a few hundred milliseconds before and after breakdown. In some measurements, charge-sensitive amplifiers and fast Ortec™ amplifiers (VT120 and 9305) were also used.

All the detectors listed above contained dielectrics between the anode and the cathode electrodes as a necessary constructional support. We observed that, in some cases, these dielectric parts could actively contribute to the breakdown either by disturbing the local electric field and emitting jets of electrons [9], or by creating current feedback loops and facilitating the discharge propagation along the dielectric surface [7].

To better interpret the prebreakdown and postbreakdown phenomena we also performed "control" studies of rate-induced breakdown with "dielectric-free" designs: An MSGC without substrate (emulator of MSGC (E-MSGC) with a 0.5-mm gap [7]) and a thin-gap (0.6-mm) PPAC without any spaces between the anode and cathode planes. Both meshes and plane electrodes were tested in this latter configuration.

III. RESULTS

It is known in general that breakdown is a complicated phenomenon involving many microprocesses and macroprocesses [12].

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Studies performed here, however, reveal some common features of rate-induced breakdowns for all micropattern detectors tested, regardless (as a first approximation) of whether or not they contained dielectric parts between their electrodes.

In the next section we will present a general overview of these results.

A. Low Rate (<1 Hz/mm^2)

As was already described in reference [9], breakdowns occur at low rates in most cases through a streamer mechanism. In this work, this observation was confirmed for a large variety of gases. In addition, it was demonstrated that streamer-type breakdowns take place in MICROMEGAS and in thin-gap PPAC's. Thus, in well-quenched gases, streamers were the main mechanism of breakdown in micropattern detectors.

Further, we found that, in the case of dielectric-free detectors (E-MSGC's and thin-gap PPAC's) and also MICROMEGAS, breakdowns appeared at some certain gas gain, A, such that $An_0 \sim 10^8$ electrons, where n_0 is the number of primary electrons created by the primary ionization. This limit coincides with the well known Raether limit [12], [13]. We demonstrated that this Raether limit is valid for other micropattern detectors too [6], a conclusion that has recently been confirmed by others [14] for all micropattern detectors with dielectrics, including double-step GEM's.

It was found that, in the case of detector designs with dielectric between the electrodes, the Raether limit was valid only for large n_0, as, for example, in the case when the primary ionization was produced by alphas. In the case of small n_0, breakdown may occur at lower gains than expected from the Raether limit due to discharges along the dielectric surface.

In poorly-quenched gases at high gains one could very occasionally observe photon or ion feedback. When the electrodes were directly exposed to the light from the avalanches, photon feedback may have appeared in some gases. A relevant example of a detector dominated by photon feedback would be a thin-gap PPAC or MICROMEGAS operating in, for example, Ar/(10–20 percent)CO_2 or Ar/(10–20 percent)N_2, when we clearly recorded that the maximum achievable gain was limited not by streamers, but by multiple avalanche generation. When the cathodes of detectors were somehow “hidden” from direct photons, like in the MSGC, the probability of photon feedback from the cathode was very low, but then ion feedback could be observed in poorly-quenched gases.

We also observed and studied another significant phenomenon that we termed “‘memory effect.” The memory effect means that, after breakdown, one cannot apply the previous voltage for seconds, or sometimes minutes. This effect was observed for all detectors studied in both this and our previous work [15]. The duration of this dead time depends very much on the gas and surface conditions. Immediately after this dead time one can observe spontaneous electron emission in the form of jets containing ~10 electrons each [7].

This is a very insidious effect, since one may have to wait a long time for the full restoration of gain after breakdown.

B. High Rates (>10 Hz/mm^2)

We confirmed our earlier observations that for all gaseous detectors the maximum achievable gain always drops with rate. As a results of these studies one can suggest a general figure for the maximum achievable gain vs. rate as shown in Figure 1.

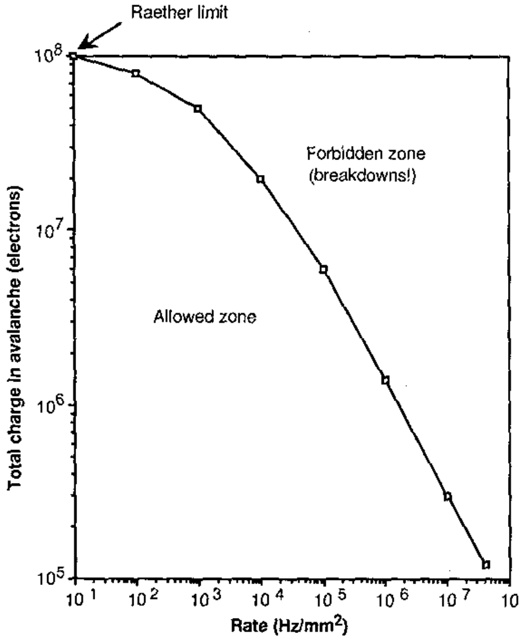

Figure 1: General curve reflecting gain limitation with rate for gaseous detectors.

It was also discovered, for all detectors tested, that the rate-induced breakdown occurred through what we termed a “preparation” phenomenon: From a few hundred nanoseconds to hundreds of milliseconds before breakdown there appeared, in the current oscillograms, either spikes or a steady growth as shown in Figure 2a and 2b. Of these spikes there were two types: One was very short (<20 ns) and contained many (>100) electrons, and these we termed “bursts;” the other were relatively long series of small, separate, pulses containing ~10 electrons and these we called “jets.” Similar phenomena were observed earlier at high rates for thick-gap PPAC's [16]. The intensity of these pre-breakdown phenomena depended on the gas mixture, and for a given mixture increased sharply with the increasing electric field on the cathode. The preparation activity (number of current spikes before breakdown or a spontaneous current increase) was highest in isobutane mixtures. The “quietest” mixture was Ar/CO_2. One can state that in most cases this “preparation” is not related to any feedback mechanism because usually it is not correlated to any drift time (electrons or ions), is not periodic, and also has very random pulse amplitudes. Note that in the case of classical feedback one observes periodic pulses (with a period equal to the drift time of electrons or ions) with amplitudes that increase or decrease monotonically with time [12].

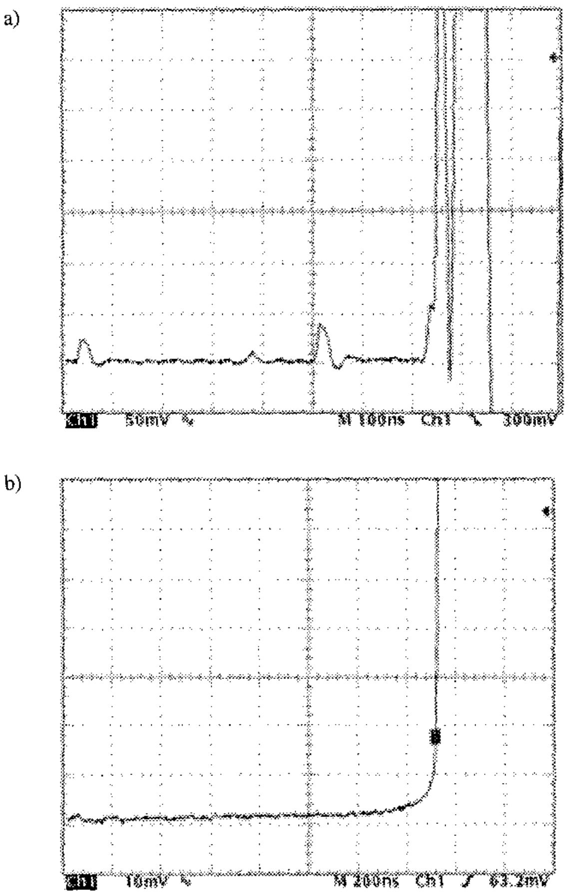

Figure 2 (a, b): Two typical oscillograms showing a preparation mechanism immediately preceding a high-rate breakdown.

The memory effect in rate-induced breakdowns is strongly pronounced and may last for hours. The duration of the "dead" time depends very much on the gas. It is longest in isobutane mixtures (up to many hours and even days!) and shortest in Ar/CO_2 (much less than seconds). This is an important phenomenon for practical applications where one could have to wait a long time for full restoration of normal detector operation.

In the case of the thin-gap PPAC and MICROMEGAS we found a strong correlation of the memory effect with the aging properties of the gas mixture: The more sensitive a mixture was to aging (like isobutane), the longer was the dead time.

After observing this correlation we noted an interesting phenomenon: After changing gas mixtures from one containing isobutane to Ar/CO_2 the same dead time (i.e. that for isobutane) was observed after the first breakdown. For infrequent breakdowns this dead time remained unchanged for hours. However if one initiated continuous breakdowns for a few seconds, then the dead time sharply decreased and finally approached the dead time typical for Ar/CO_2 mixtures. We called this "cleaning by discharges."

C. Intermediate Rates ($\sim$1–10 Hz/mm^2)

At these rates a mixture of the phenomena described above was observed.

IV. DISCUSSION

As follows from the previous sections, one can clearly distinguish two distinct breakdown cases: those of low rates and those of high rates.

A. Low Rate

We found that at low rates the breakdown in micropattern detectors occurs through one of the classical breakdown mechanisms as in "usual" gaseous detectors:

1) through a streamer mechanism
2) by a photon feedback loop
3) through an ion feedback loop.

In well quenched gases, streamer breakdown occurs at some critical total charge in the avalanche, $An_0 \sim 10^8$ electrons. It is very surprising that the Raether limit remains valid for the micropattern detectors, as this limit was originally established only for thick-gap PPAC's of a few millimeters or more [12], [13]. In this case, after the fast collection of electrons from the avalanche, positive ions remain in the discharge gap (for the ion drift time), and this may create the critical space charge necessary for streamer formation [17]. In the case of thin-gap detectors, the ions are removed very fast (for example, for MICROMEGAS the ion removal time is ~100 ns) and the accumulation of critical space charge is therefore impossible.

Also, streamers appear at some critical total charge in the avalanche, this condition sometimes cannot be reached for detector designs with dielectrics because at small n_0 one has to work at elevated voltages where surface discharges appear. As a result, these detectors will operate at gains less than that deduced from the Raether limit. It is interesting to note that these surface discharges also have streamer mechanisms. In a very narrow voltage interval they are quenched and could be observed experimentally as "noise" pulses [7], [9]. At higher voltages they transit rapidly to sparks.

A second reason why breakdowns in micropattern detectors may appear at lower gains than deduced from the Raether limit could be a photon or ion feedback loop. The conditions for these breakdowns are $AG_{ph} \sim 1$ or $AG_+ \sim 1$, where G_{ph} and G_+ are the coefficients of the respective secondary processes [12]. Feedback in micropattern detectors may appear even in gas mixtures which are traditionally considered as quenched, for example in Ar/CO_2. This is because, for a given gas mixture, the degree of quenching depends also on detector geometry, since it depends on the mean free path of the ultraviolet photons from the avalanche, and the mean length over which the positive ions of the noble gas ionize the quencher molecules by transfer mechanisms.

Therefore, in order to reach the Raether limit, which offers the highest possible gains at low rates, one should optimize not only micropattern detector designs, but also gas mixtures.

B. High Rate

As already mentioned above, the rate-induced breakdown in thick-gap PPAC's was studied in reference [16]. It was demonstrated that at high rates, breakdown occurs through a "preparation" mechanism.

In this work we found exactly the same phenomenon was present in thin-gap designs and this was true for designs with and without dielectric between the anodes and cathodes.

Therefore, at high rates, a new mechanism of breakdown appears: jets and bursts, both for designs with and without dielectric. The most probable reason for these jets and bursts is thin dielectric films on metallic cathode surfaces [18]. These dielectric films could be dielectric inclusions, adsorbed layers, or a polymer layer created for instance by polymerization of the quencher gas by avalanches or by precedings discharges. Positive ions from the avalanche deposited on these films create extremely high electric fields inside (Malter effect). These electric fields cause electrons from the metal to start to penetrate the dielectric films (see Fig. 3a.). After some accumulation time, an "explosive" process occurs, and electrons are ejected from the films in the form of bursts or jets [18] (see Fig. 3b). Positive ions on the surface also reduce the work function so that G_{ph} and G_+ will be increased [19], [20].

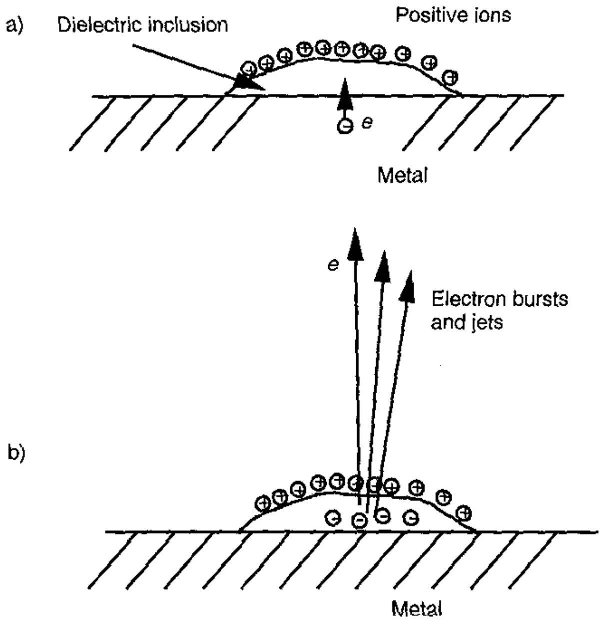

Figure 3: Schematic illustration of a two-step process which leads to emission of jets and bursts from thin dielectric films.

Of course, during the deposition of ions on the surface of the dielectric films, there will be some leakage of ions to the surrounding metals and also ion neutralizations. So, the absolute density of ions on the surface will be determined by the dynamic equilibrium.

If there is zero surface leakage, then field emission reaches a maximum when the deposited charge equals the surface charge. From the electric fields typical for micropattern detectors, one can estimate the surface charge. One can calculate at what total charge in the avalanche the deposited charge density will be equal to the surface charge density, and this will give $\sim 10^8$ electrons per avalanche size. Perhaps this value can be somehow related to the validity of the Raether limit for micropattern detectors at low rates (see discussion in a previous section).

The qualitative model presented above also explains the memory effect. After breakdown there are positive ions remaining on the dielectric inclusions and films, causing emission of electrons and also an enhancement in G_{ph} and G_+, and this produces a lower breakdown threshold for a time necessary for the ions to leak or for the film to disappear (by sublimation for example). Further, this explains the dependence of dead time on the polymerization (aging) properties of the gas mixture and also the "cleaning by discharge" (or in another words destruction of the polymerized film by discharges) in non-polymerized mixtures.

One cannot exclude the fact that these jets and bursts also create some local feedback: Avalanches started by jets close to the cathode create ions or photon feedback due to a significant reduction of G_{ph} and G_+.

Note that not only metals covered with thin dielectric films but also "pure" dielectrics can emit electrons under ion bombardment [9]. This is a well known effect which causes "noise" pulses in resistive plate chambers [21].

V. POSSIBLE WAYS FOR IMPROVEMENTS

As follows from the above discussion, in order to improve a detector's gain/rate characteristics one should work in non-aging gases and reduced fields. In the case of Ar/CO_2 we were able to considerably improve the rate characteristic of thick-gap PPAC's as shown in Figure 4. Unfortunately in the case of thin-gap detectors, this non-aging mixture is too transparent for the photons from the avalanche and so high gains were impossible to reach due to photon feedback. However, these results indicate that there is room for gas optimization.

The other way to reduce the probability of burst and jet emission is to lower the electric fields on the cathode surface. This could be done by optimization of electrode designs or by using double-step designs where, for the same overall gain, each step can work at a reduced field [14]. The other interesting example could be designs of the MICROMEGAS type. Our measurements show that in MICROMEGAS positive ions from the avalanche are collected, mostly not on the inner surface of the cathode mesh, but on it's outer surface facing the drift region. The electric field at this outer surface is relatively low (compared to the inner part) and this reduces the probability of preparation phenomena. Probably this allows these detectors to reach the gain limits at high rates (plotted on Fig. 1) even in polymerization-prone gases.

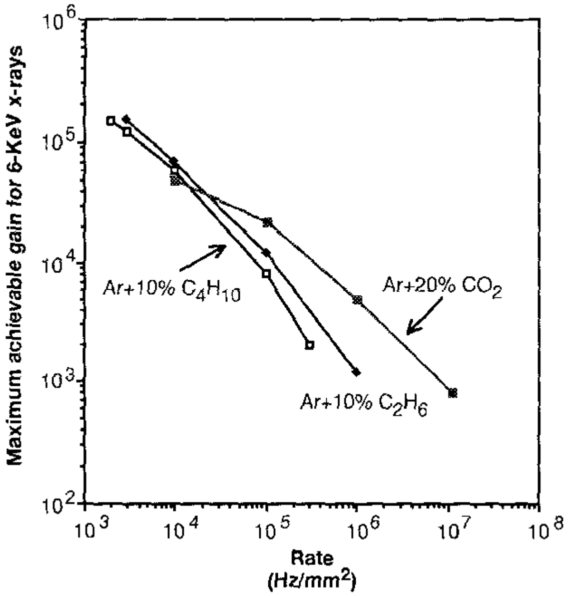

Figure 4: Improvement in the rate characteristics of a PPAC by optimizing the gas mixture.

VI. CONCLUSION

The conclusion of this study is simple: There are two fundamental gain limitations for all gaseous detectors. These are:

1) at low rate—the Raether limit
2) at high rate—the gain drops with rate.

It is practically impossible to overcome these limits when one operates at 1 atm. Some small improvements are available through optimization of the gas mixture or by developing designs with reduced electric fields near the active part of the cathodes. These optimizations will allow some detectors with poorer characteristics to approach the limits defined above and also to reduce the duration of the "memory effect" time after breakdowns.

VII. REFERENCES

[1] A. Oed, "Position-sensitive detectors with microstrip anode for electron multiplication with gases," *Nucl. Instr. and Methods in Phys. Res.*, vol. A263, pp. 351–359, 1998.

[2] F. Angelini et al., "The micro-gap chamber," *Nucl. Instr. and Methods in Phys. Res.*, vol. A335, p. 69, 1993.

[3] F. Bartol et al., "The CAT. Pixel proportional gas counter detector," *J. Phys. III France*, vol. 6 pp. 337–347, 1996.

[4] Y. Giomataris et al.,"MICROMEGAS: a high granularity position-sensitive gaseous detector for high particle flux environments," *Nucl. Instr. and Methods in Phys. Res.*, vol. A376, pp.29–35, 1996.

[5] F. Sauli, "GEM: a new concept for electron amplification in gas detectors," *Nucl. Instr. and Methods in Phys. Res.*, vol. A386, pp. 531–534, 1997.

[6] Y. Ivaniouchenkov et al., "Breakdown limit studies in high-rate gaseous detectors," *Nucl. Instr. and Methods in Phys. Res.*, to be published.

[7] V. Peskov et al., "Feedback and breakdown in microstrip gas counters," *Nucl. Instr. and Methods in Phys. Res.*, vol. A397, pp. 243–260, 1997.

[8] P. Fonte et al., "A study of breakdown limits in microstrip gas counters with preamlification structures," *Nucl. Instr. and Methods in Phys. Res.*, vol. A416, pp. 23–31,1998.

[9] V. Peskov et al., "Breakdown features of various microstrip-type gas counter designs and their improvements," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 244-248, 1998.

[10] G. Charpak et al., "First beam results with MICROMEGAS, a high-rate, high-resolution detector," *Nucl. Instr. and Methods in Phys. Res.*, vol. A412, pp. 47–60, 1998.

[11] P. Fonte et al., "Rate and gain limitations of MSGC's and MGC's combined with GEM and other preamplification structures," *Nucl. Instr. and Methods in Phys. Res.*, to be published.

[12] H. Raether, Electron avalanches and Breakdown in Gases, Washington, Butterworth, 1964, pp. 1–253.

[13] P. Fonte et al., "Feedback and breakdown in parallel-plate chambers," *Nucl. Instr. and Methods in Phys. Res.*, vol. A305, pp. 91–110, 1991.

[14] A. Bressan et al., "High rate behavior and discharge limits in micropattern detectors," *Preprint CERN-EP/98–139*, September 1998.

[15] V. Peskov et al., Reported at the Vienna Wire Chamber Conference, Vienna, February 1998.

[16] Y. Ivaniouchenkov et al., "The high-rate behavior of parallel mesh chambers," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 258–262, 1998.

[17] P. Fonte et al., "Streamers in MSGC's and other gas counters," *Preprint SLAC-PUB-7718*, 1987.

[18] R. Latham, High Voltage Vacuum Insulation, New York, Academic Press, 1995, pp. 1–663.

[19] G.F. Karabadjack et al., "Coordinate gas counters with superhigh energy resolution for plasma diagnostics," *Nucl. Instr. and Methods in Phys. Res.*, vol. 217, pp. 56–64, 1983.

[20] I.E. Chirikov-Zorin et al., "On sensitivity of gas-discharge detectors to light," *Nucl. Instr. and Methods in Phys. Res.*, vol. A371, pp. 375–379, 1996.

[21] P. Fonte et al., "A new type of spark-protected parallel mesh chamber," *Nucl. Instr. and Methods in Phys. Res.*, to be published.