Streamers in MSGC's and other gaseous detectors

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ABSTRACT

In this paper we describe the formation and propagation of streamers under different conditions and in different gas mixtures. We discuss how streamers may limit the operational capabilities of various gaseous detectors.

1. Introduction

Wire chambers, proposed by G. Charpak *et al.* [1], revolutionized detector development. They are widely used now in many experiments and have made possible many important discoveries in High Energy Physics. A further significant step was made by A. Oed et al. [2], who suggested replacing the wires by strips on a dielectric substrate.

This detector, the MSGC, has many technological advantages. However, it suffers from one main disadvantage: at gains of about 10^4 sparking appears and this is a serious limitation in many applications. Recent studies have shown that the gain is limited by the appearance of streamers [3] and that these streamers have a very narrow self-quenched region (in voltage) and then transit rapidly to sparks.

Do streamers affect the rate characteristics of MSGC's and other gaseous detectors and can breakdown in MSGC's be prevented? In this paper we will try to answer these questions.

2. What is known about streamers

2.1 PPAC

Historically, the first observations and systematic studies of streamers were done in Parallel-Plate Avalanche Chambers (PPAC's) [4] and we will summarize here the main conclusions.

At high gains in gaseous detectors two changes occur in the avalanche dynamics:

1) photons start to contribute to the avalanche development and cause a spread of the avalanches.
2) the space charge in the avalanche becomes sufficient to disturb the external electric field.

As a result, photoelectrons created outside the avalanche start to move towards it - Fig. 1. This may cause a growth of the avalanche in all directions and finally a streamer (a thin plasma filament) is formed. This occurs at some total charge in the avalanche (usually 10^8 electrons) corresponding roughly to the charge density at which the space-charge field becomes comparable to the applied field. This value seems to be an universal one in parallel-plate geometry at pressures close to or larger than 1 atm and is known as the Raether limit [4,5].

In any given gas mixture and pressure, streamers seem to propagate only in regions with applied fields larger than some critical value.

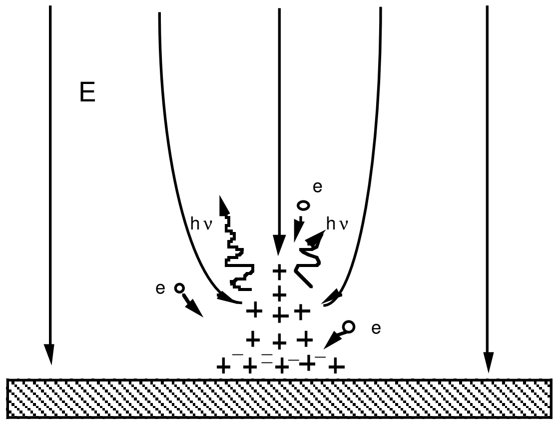

Figure 1 - Schematic drawing of streamer development.

Experimental studies [6] show that a streamer in its final stage has a structure very similar to a glow discharge. Note that in glow discharges an essential mechanism for sustaining the plasma is electron emission from the cathode spot and multi-step ionization in a positive column, i.e. ionization from excited states of atoms and molecules by electron impacts. Some authors [7] suggested that multi-step ionization also plays an important role in streamer formation. This helps to explain the propagation of streamers in gases with high concentrations of quencher when the photon mean free path is too small for photoelectrons to get sufficient multiplication.

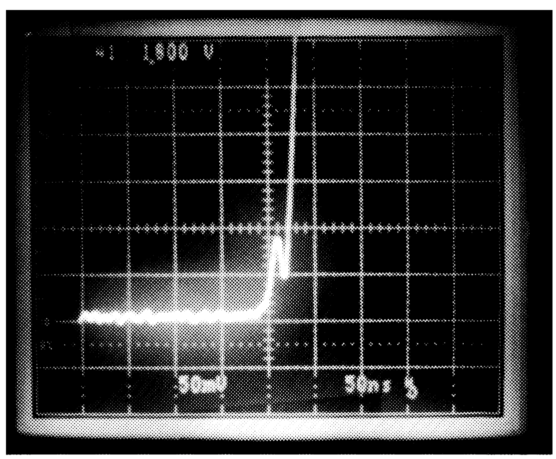

Figure 2 - Typical current pulse during breakdown in a PPAC [5].

When streamers reach the opposite electrode they may cause a powerful spark. In this case one observes precursors corresponding to the primary avalanche and then, with some delay, a current pulse corresponding to the propagation of the streamer and finally to the spark (see Fig. 2).

Many authors attempted to calculate the dynamics of avalanche to spark transition. Although models of streamer formation and development seem to reproduce well the experimental data [8], there is no comprehensive theory describing a streamer's transition to a spark when it touches the electrode [9]. It may be strongly dependent on electrode conductivity and surface conditions.

The main advantage of the PPAC is the ability to reach high gains (as was mentioned above the total charge in the avalanche before breakdown appears is usually about 10^8), and high rate capabilities ($>10^5$ counts/mm^2 sec). However, this total charge in the avalanche before breakdown is achievable only at rather low rates. At higher rates, the breakdown gain is usually inversely proportional to the counting rate. One possible reason for this is that avalanches overlapping in time and space effectively add their respective ion charges [5].

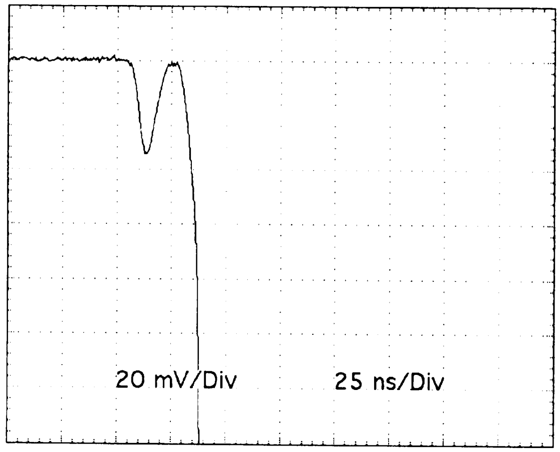

Figure 3 - Current pulse at breakdown in a RPC [11].

2.2 Streamer chambers

Streamer development in PPAC's can be restricted if a very short duration high-voltage pulsed is applied. This principle was realized in the so called "streamer chambers", which were actively used in many experiments [10]. The streamer chamber works in a "waiting" mode. A passing charged particle produces ionization inside the chamber and also generates a signal in a trigger system located outside the detector volume. This signal in turn triggers a short (~10 ns) high-voltage pulse, which initiates streamer development. Since the high-voltage pulse is very short, streamers are generated very close to the position of the initial ionization and do not produce any sparks. Such streamers emit enough light to be recorded optically which allows reconstruction of the track. If a longer duration high-voltage pulse is applied, streamers transit to sparks. This principle is realized in the so called “spark chambers” [4].

2.3 RPC

In Resistive Plate Chambers (RPC's) one or both electrodes are made from materials with high resistivity (usually > 10^{10} Ω cm).

In principle there should be no significant difference in streamer formation and their initial development between the PPAC and the RPC. Indeed, the same current pulse features were observed in both the RPC and the PPAC-see Figs. 2 and 3 [5,11,12]. However, the final streamer stages and especially the power dissipated in the sparks is different. Roughly speaking, the power dissipated in sparks depends on the effective discharge capacities. In the case of metallic electrodes a considerable part of the charge accumulated in the detector will be discharged through the spark.

In the case of the RPC local charging of the resistive electrode by the spark current renders the effective capacitance very low. As a consequence, sparks created by streamers in the RPC will be weak. This is why in many papers these weak sparks were called "streamers " although they are not actually real streamers.

Power dissipated in sparks also depends on the gas mixture. For example, in freon mixtures the electron charge released by a spark could be very small, about 1 pC [13].

For RPC’s the maximum achievable gain is also inversely proportional to the counting rate, but this dependence is much steeper than in the case of the PPAC. The primary reason for this dependence is not the appearance of breakdown due to avalanche overlapping, but simply charging of the dielectric electrodes of the RPC. The best rate characteristics, so far, were obtained with Pestov (electronic) glass electrodes [14]. Spatial resolutions achieved with such detectors were better than 0.1 mm. Note that when metallic readout strips were placed inside the gas gap between the electrodes the rate capability approached that of the PPAC [15].

2.4 Detectors with anode wires

2.4.a Single wire counter and multiwire chambers

As was described above, in uniform fields streamers are usually unquenched and once started continue to develop until they touch the opposite electrode.

It was found that streamers also can be formed in detectors with non-uniform fields, for example in single wire counters and multiwire chambers (MWPC) [16,17]. The main feature of these streamers is that they start to propagate perpendicularly to the anode wire, but usually they do not reach the cathode due to the fast field drop with distance from the anode (see Fig. 4). As a consequence they do not trigger sparks and are somehow "self quenched". Note that these streamers appear only in detectors with rather thick anode wires (>50 μm). In the case of thin wires, the field drops so fast with distance that at high gains discharges start to propagate along the wire (the so-called Geiger or limited-Geiger mode) [18].

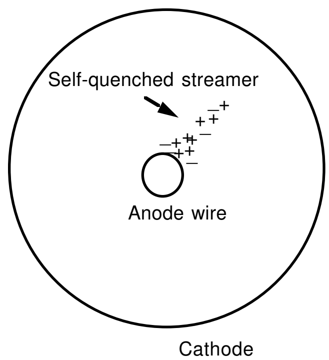

Figure 4 - Self-quenched streamer in detectors with thick anode wires.

How do these self-quenched streamers reveal themselves experimentally?

When streamers appear one can observe a jump in amplification, as shown in Fig. 5. The other typical characteristic of streamers is an intense (>10 μA) and short (<50 ns) current pulse. In some cases streamers can be recorded optically.

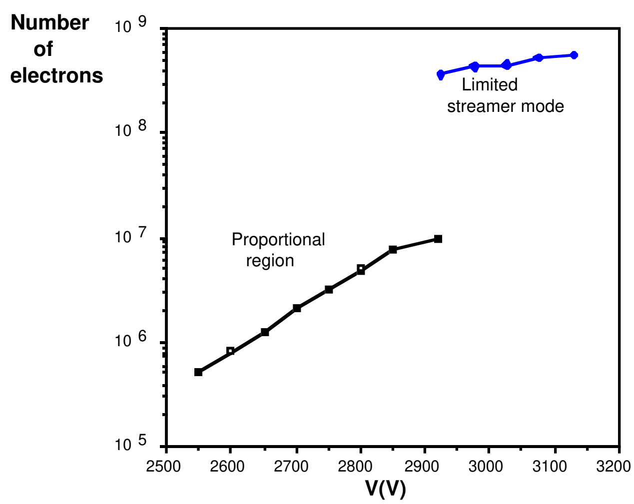

Figure 5 - Total charge in avalanche vs. voltage in wire detectors operating in proportional and streamer mode [17]

The gas gains at which streamers appear depend not only on the detector geometry, but on the gas mixture and pressure - see Figs. 6a and 6b. From this figure one can see that there is an optimum concentration of the quencher at which the gain reaches the highest values.

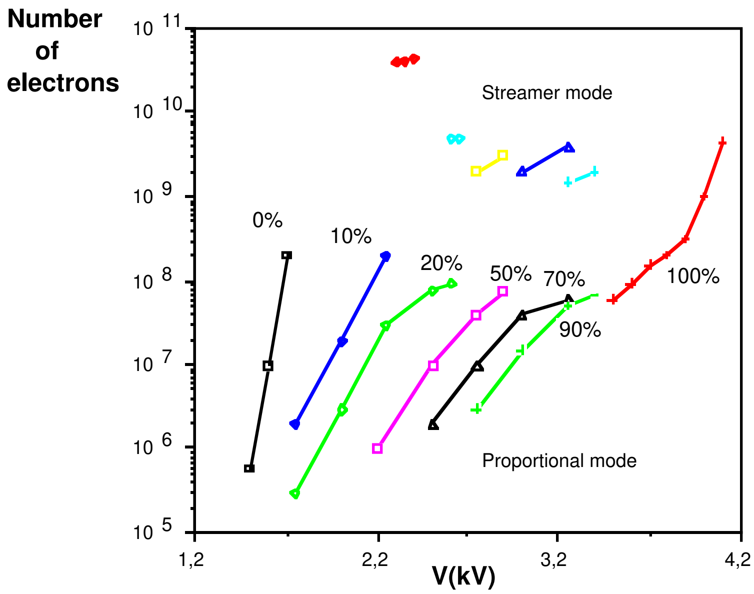

Figure 6 a - Total charge in avalanche at which streamers develop in a single wire counter for various methane concentrations in Ar/CH_4 mixtures [19]

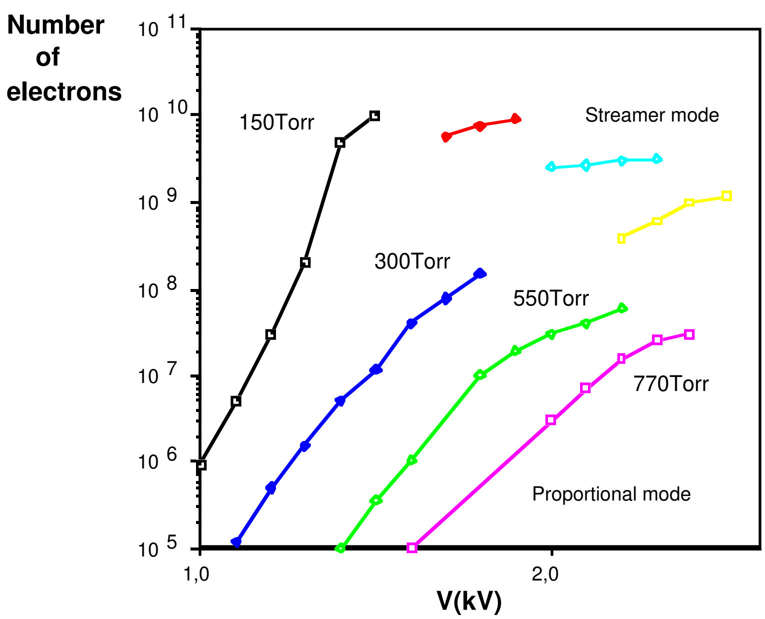

Figure 6 b - Total charge in avalanche at which streamers develop in a single wire counter for various total pressures in Ar + 25% iC_4H_{10}.

The maximum charge in avalanches at which streamers appear also depends on noble gas: it is maximum in He and Ne-based mixtures and minimum in Xe-based mixtures (see Fig.7)

In [19] it was claimed that in some pure quenching gases at 1 atm, CH_4 for example, no streamers develop at all (see Fig. 6a). The same is also true at low pressures (p<0.3 atm) for most of the mixtures tested in [19] (see Fig. 6b).

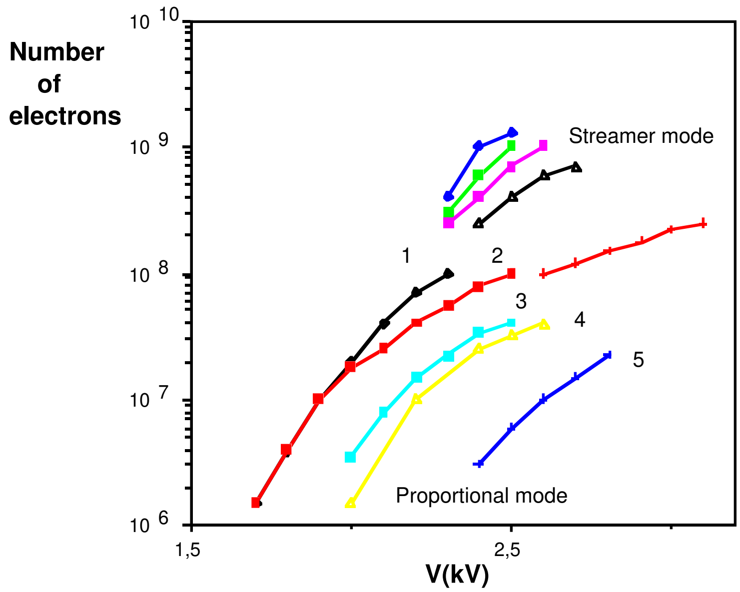

Figure 7 - Total charge in avalanche at which streamers appear in various noble gases [19].
1 - He + 25% iC_4H_{10} 2 - Ne + 25% iC_4H_{10}
3 - Ar + 25% iC_4H_{10} 4 - Kr + 25% iC_4H_{10}
5 - Xe + 25% iC_4H_{10}

2.4.b Streamers in asymmetric wire chambers

Asymmetric wire chambers are the next generation of detectors and were invented to improve the rate capability of the MWPC [20]. In fact, they have a geometry similar to the MSGC, but the strips are replaced by wires and there is no substrate. A short distance and strong field between anodes and cathodes allows fast removal of positive ions.

In asymmetric wire chambers streamers may also occur at total a charge in avalanche larger than about 2-5×10^6 electrons [3,21].

3. Streamers in gaseous detectors with substrate

3.1 Streamers in asymmetric wire chamber with substrates

What will happen when we place the wires of the asymmetric wire chamber in direct contact with a dielectric surface? In this case streamers also occur (at a total charge in avalanche slightly less than without substrate), but they are unquenched. So the presence of the surface changes the streamer's development.

Self-quenched streamers are only observed occasionally, at low gains. Note that wires should be in firm contact with the surface otherwise charging will occur and the gain will drop with time [22].

3.2 Streamers in uncoated MSGC's

It was discovered recently [3] that in the case of MSGC's the maximum achievable gain is also limited by streamers, as in asymmetric wire chambers with substrates. A typical waveform of the current pulse of a streamer in a MSGC is presented in Fig. 8. Usually the streamer current pulses are shorter than 50 ns and have amplitudes up to a few mV on 50 Ω.

In some gases, for example with TMAE vapor, the streamers were clearly observed visually in a dark room (note that in this case the gas chamber with MSGC and all gas system was heated to 40 C° to increase the partial pressure of TMAE). As in the case of the asymmetric wire chamber with substrates, streamers in MSGC's have a very narrow (in voltage) self-quenched region and then transit rapidly to sparks. These sparks were very bright and could be seen easily even in an illuminated room.

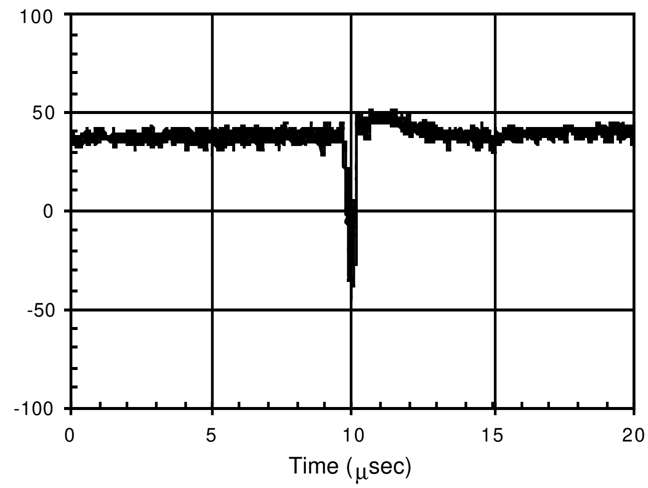

Figure 8 - Streamer current pulse in a MSGC (on 50 Ω).

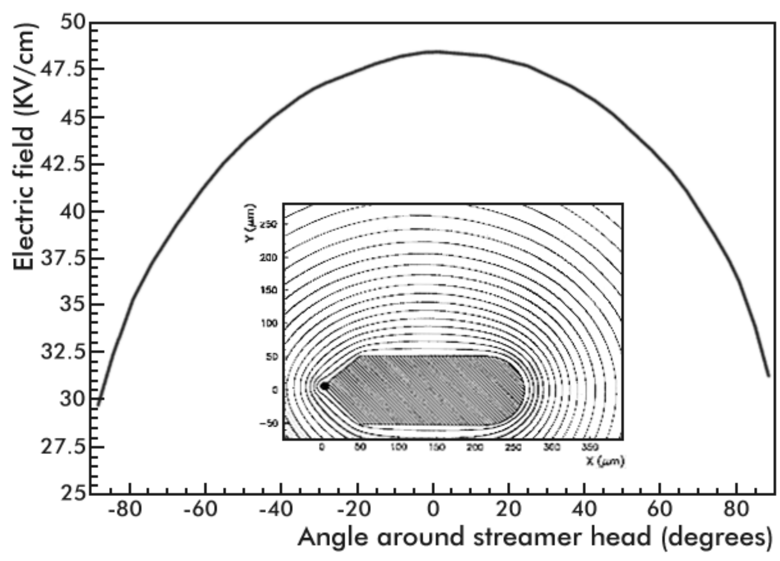

Figure 9 a - The field strength around the tip of a streamer. The inset details a map of equipotential lines for a streamer near an anode wire.

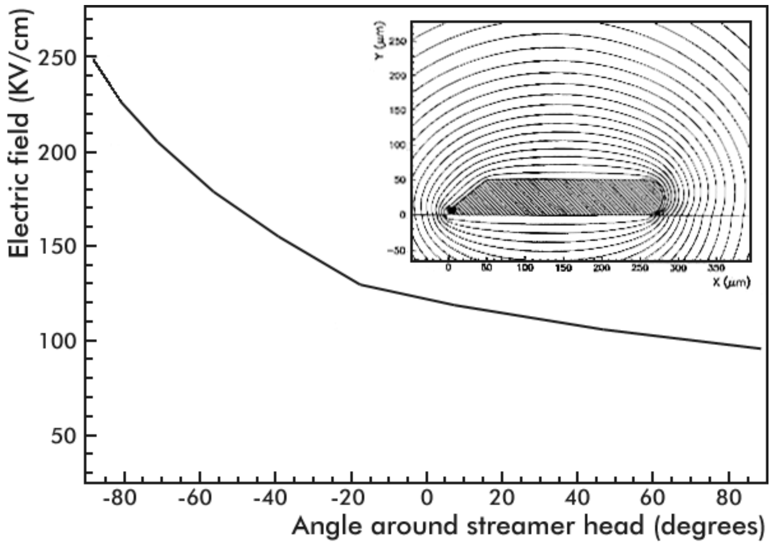

Figure 9 b - The same for a streamer in the presence of a surface.

Why are the streamers unquenched in the presence of a substrate?

This can be understood from calculations of the field near the streamer head. In these calculations the streamer was considered as a conductive medium (plasma actually), kept at the anode potential.

Figs. 9a and 9b show calculations of the field near the streamer (diameter 100 μm, length 250 μm) for an asymmetric wire chamber without and with substrate. One can clearly see that when the substrate is present there is a high local electric field between the head of the streamer and the substrate, due to dielectric polarization. This is therefore the region of the most intense ionization during the streamer propagation. Thus, the streamer, when it is close to the dielectric surface, creates the high field necessary for its own propagation.

These streamers are very similar to the well known "gliding" discharges [23]. Gliding discharges are two dimensional and, due to the extreme "sharpness" of the edges of the surface space-charge layer, the transition from surface avalanche to the spark type of breakdown occurs at much lower electric fields than in the usual "three dimensional" case [23].

Calculations also show that points where the metal electrode structures touch the dielectric substrate have a very high electric field. These points are favorable for the initiation of avalanches close to the surface and the formation of surface streamers.

Are there any ways to limit streamer formation? This could be done by optimization of the MSGC and by developing substrate-free detector designs.

3.3 Optimization of uncoated MSGC's

As was described above, in the case of detectors with thin anode wires (< 20 μm) streamers cannot touch the cathode due to the fast drop of radial electric field. By analogy one can think that in order to suppress the streamers and therefore increase the maximum gain before breakdown in the MSGC, the multiplication region should be concentrated to a narrow region around the anode strips and that the gas gain elsewhere should be maximally suppressed.

Of course, the real situation is more complicated because streamers create their own field. Since the calculations of streamer dynamics is rather complicated the easiest way to check the validity of our assumption is experimentally. One can try to concentrate the multiplication near the anode strips in several ways: by reducing the anode width, by increasing the anode-cathode gap and by using mixtures having a sharp dependence of gain vs. voltage. A systematic experimental study performed recently fully confirms that optimizing these parameters allows higher gains to be reached in MSGC's (see [24] for more details). As an example, Fig. 10 presents results obtained with different pitches and anode widths.

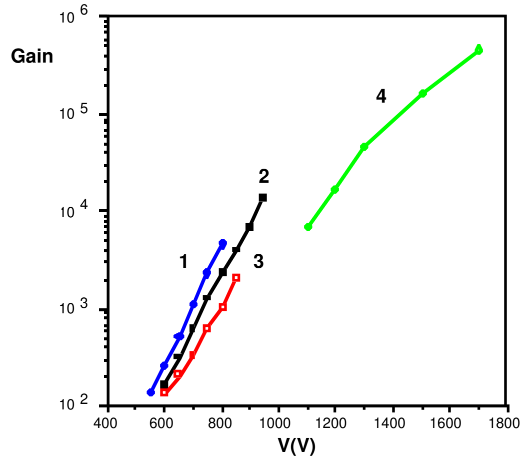

Figure 10 - Maximum achievable gains in MSGC's with different anode widths and pitches:

1 - 1 mm pitch, 10 µm anode width

2 - 2 mm pitch, 10 µm anode width

3 - 1 mm pitch, 25 µm anode width

4 - strips and wires on substrate at 2 mm pitch (see Fig.12).

One can clearly see that the highest gains were achieved with narrow anodes and at high pitches. In Fig. 11 are presented the gain vs. voltage curves for Ar/CH_4 mixtures and different concentrations of CH_4. One can see that the maximum achievable gain behaves similarly to what was observed in a single-wire counters (see Fig. 6). The highest gains in this particular mixture were achieved in pure CH_4. This result is in excellent agreement with those obtained for streamers in single-wire detectors - see Fig. 6.

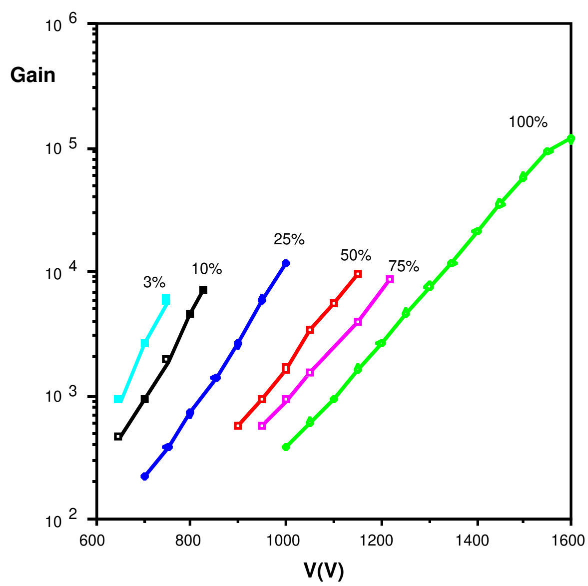

Figure 11 - Maximum achievable gain in an MSGC operating in Ar/CH_4 mixtures for various CH_4 concentrations

It was found also that the maximum achievable gain depends on the noble gas [25]. The highest gains were achieved in He and Ne-based mixtures and lowest in Xe-based mixtures. These results are in a good qualitative agreement with those obtained with single wire counters (see Fig. 7).

Despite the good qualitative agreement between streamer onset properties in MSGC's and single wire detectors the charge needed for streamer development is two orders of magnitude lower in the former case. This may be attributed to the two dimensional nature of the streamer discharge in MSGCs, which will be more concentrated than the three dimensional streamer formed in single wire detectors.

New geometries of microstrip detectors were also tested. In one of these, cathodes were made from thick wires of diameter 0.75 and 1 mm touching the surface or suspended just above it (see Fig. 12). In such designs, we tried to minimize the contribution of the substrate and reduce the field near the cathode. The gain achieved with such devices was 10^5 or higher (see Fig. 10 - curve 4). All these results confirm the assumption that the gain should be concentrated near the anodes.

As a result of this work on MSGC's optimization, the authors of ref. [26] were able to get a uniform gain of 10^4 over a MSGC of surface area 30×30 cm^2 with 2 mm pitch, 10 μm anodes strips and a Penning mixture (Xe+2% isobutylene at 2 atm) having a sharp dependence of gain vs. voltage. The probability of breakdown is proportional to the detector's surface area. However, not a single breakdown was observed over a week of continuous operation of the detector at this gain.

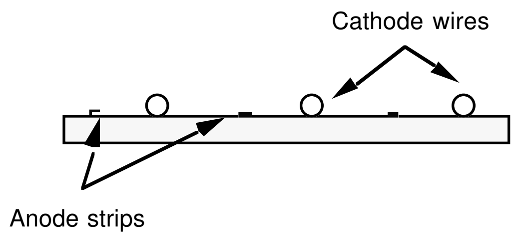

Figure 12 - Example of a MSGC design which permits the highest gains.

3.4 Streamers in coated MSGC's

At high counting rates the dielectric substrate of the MSGC's is charged by positive ions from avalanches causing gain variations with time. One solution to this problem is coating the substrate with a thin, higher conductivity layer (e.g. diamond). In MSGC's with conductive coated substrates the mean field along the surface between anodes and cathodes increases and, what is even more important, becomes more uniform [22]. This is favorable for streamer propagation and as a result the maximum achievable gain is lower compared to bare MSGC's.

Another feature of coated MSGC's is high amplitude spurious pulses which can also trigger breakdown. The nature of these pulses is discussed in [22,27].

3.5 Microgap Gas chambers

The Microgap Gas Chamber (MGC) was developed by F. Angelini *et al* . [28] in an attempt to solve the charging problem of MSGC. The main feature of this type of detector is a very short gap between anodes and cathodes allowing fast removal of ions produced by avalanches. As a result no charging effect was observed even at rates up to 10^7 counts/mm^2 sec. However the maximum achievable gain is also limited to 10^4.

Our recent results with MGC's [29] reveal many similarities with MSGC pre-discharge features. We concluded that breakdown in these detectors occurs through a streamer mechanism as in MSGC's. It is not surprising since part of the avalanche touches the dielectric surface and may form a surface streamer.

It is interesting to note that the maximum achievable gain in the MGC depends on the gas mixture in a way similar to high pitch MSGC's. There is also one optimum concentration of quencher at which the gain reaches a maximum, and the highest gains were achieved in He and Ne-based mixtures, the lowest in Xe-based mixtures [30].

4. New types of high-rate gaseous detectors.

The low achievable gains in ordinary MSGC's stimulated different groups to develop another designs of high-rate gaseous detectors. A relevant example could be the Microdot Gas Avalanche Chamber [31,32]. The main feature of this design is that the anodes are metalized dots on a substrate and the cathodes are coaxial rings. This geometry insures fast drop of electric field with distance from the anode dots and as a consequence allows higher gains ($> 10^4$) to be achieved [32]. However, even in this design streamers may develop at high gains as was clearly shown in [31].

Another example of a new high-rate detector could be the recent MICROMEGAS [33]. MICROMEGAS is just a PPAC with a small (~0.1 mm) gap between electrodes. There are at least two advantages of this design:

1) the small size of the gap and hence the avalanche reduces the effective area of the induced charge on the anode strips. Thus by using small pitch strips a better position resolution in principle could be achieved,
2) a small gap also guaranties a fast removal of positive ions and hence less space charge effect at high rates.

MICROMEGAS permits gains of 10^4-10^5 [34]. At higher gains breakdown appears, presumably through the streamer mechanism. However in a new design with narrow anode strips it was possible to explore additional multiplication in non-uniform field near the anode strips, permitting an additional factor of 5 or more in gain [34].

Other examples of new high rate gaseous detectors in which the role of substrate was minimized could be CAT [35] and GEM [36]. In these detectors amplifications occur in "holes" in substrate. There were no reports on breakdown studies in these devices, but since part of the avalanche touches the dielectric surface one can assume that it may occurs through the surface type of discharge.

5. Potential limitations of high-rate gaseous detectors

In general one can assume that in any high-rate detector, fast removal of ions requires a short distance between anodes and cathodes, as well as an high and uniform field. But these are also favorable conditions for streamer development. Additionally, at high counting rate, avalanches start overlapping in space and time [5] and this lowers the maximum achievable gain at which streamers appear. This effect is also proportional to the detector surface area, so streamers always appear soon or later just due to statistics. So, large-surface high-rate detectors are specially prone to suffer from streamers.

Another effect in some types of high-rate detectors is cathode "excitation". It was observed that under ion bombardment the work function of the cathode may be reduced [37] and additionally it may emit electrons [22, 38]. This emission may continue for several minutes. Due to these effects, after one breakdown another breakdown or a series of breakdowns may appear at the same place [38]. One can stop these continuous breakdowns by lowering the working voltage for a few minutes, which is obviously not a practical solution for a high-rate device.

It looks that all high rate gaseous detectors may suffer from streamers or continuous breakdown. As a result, for reliable operation one should lower the gain at high rates.

6. Conclusion

Experience shows that all detectors are rate limited for one or another reason. We described in this paper how streamers could play an important role.

In uniform fields, or when the attached to a dielectric surface, streamers are unquenched and once started continue to develop until they reach the cathodes. As follows from this paper, in substrate-free detectors and especially in geometries providing non-uniform fields one can reach the highest gains. An example could be recent modification of MICROMEGAS where amplification in non-uniform fields near anode strips was observed [34]

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