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A VERY HIGH LIGHT-YIELD IMAGING CHAMBER

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ABSTRACT

By operating the parallel-plate imaging chamber on a non-proportional regime it was possible to increase the light yield from the gas avalanches by a factor in excess of 10^4 over the proportional operation. At this higher gain, the avalanches can easily be seen by the naked eye in a moderately lit room and recorded with CCD cameras without any image intensification. The device is operating continuously and is free of sparking. The main limitations are the existence of a detection threshold that is dependent on the primary charge density, and the large amount of current flowing in the high-gain gap, leading to ageing.

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1. INTRODUCTION

The imaging proportional chamber is a gaseous detector, based on the multistep avalanche chamber (MSAC) [1], in which the choice of operating parameters is such that the photons emitted by the electron avalanches can be exploited [2–6]. Electrons produced in the gas by ionization are drifted towards a region of high electric field, where charge multiplication occurs, accompanied by photon emission. Usually the plane of detection is viewed by an image intensifier, and the image is recorded by a solid-state charge-coupled device (CCD).

The gain of the MSAC is normally limited by the occurrence of gaseous breakdown between the gap plates, leading to the formation of a spark. The energy stored in the gap's capacitance is then discharged through the spark channel, causing a dead-time until the gap capacitor recharges through the external resistor. There is some evidence that the breakdown threshold depends on the space-charge density within the gap, and on the nature of the gas [7, 8].

To be able to operate the parallel-plate avalanche chamber (PPAC) beyond the breakdown limit, we subdivided the anode plane of the amplifying gap into a great number of individual wires, replacing the mesh normally used, but keeping a mesh cathode. High voltage is applied to each wire through a 100 M Ω current-limiting resistor. The inclusion of these resistors causes every wire to be independent, reducing the capacitance available for any individual discharge. In case of gaseous breakdown, only a small discharge occurs instead of a spark, and a succession of discharges can be formed along a particle's track, forming an image. This structure can be operated either as a spark-protected proportional MSAC or as a high-gain saturated-mode MSAC. For reasons that are explained below, we will call this mode of operation the 'streamer mode' in the remainder of the text. In streamer mode the events can be clearly seen by the naked eye in a moderately lit room, and detected with normal CCD cameras.

2. DESCRIPTION OF THE DEVICE

A schematic illustration of the device used to study the streamer operation of the MSAC can be seen in fig. 1. It is composed of a 5 cm long drift volume terminated by a first amplifying gap (5 mm), followed by a transfer gap (10 mm) and a second amplifying gap (5 mm). The lateral dimensions are 20 $\times$ 20 cm². The charges collected in the drift volume are preamplified in the first gap and transferred to the final gap where the streamers occur.

Each amplifying gap is equipped with a segmented anode comprising 320 wires, 50 μ m in diameter, and 0.625 mm apart. High voltage is applied to each wire through

a 100 M Ω current-limiting resistor, and for the second gap, extra capacitors allow an improved gain in streamer mode (see below). The first gap is operated in proportional mode, the segmented anode being used only for spark protection.

As a quencher we used triethylamine (TEA) vapours, which emit strongly in the UV region (280 nm) [9] and are easy to manipulate. The emitted UV light is converted to a visible wavelength (green) by a thin foil of plastic wavelength shifter, placed close (500 μ m) to the last mesh. The TEA light-yield in parallel-plate proportional avalanches is about 1 photon per electron [10].

For streamer operation, we used the mixture He (99.5%) + TEA (0.5%). It combines proportional gain in the first gap with a sufficiently small breakdown threshold in the second gap for easy triggering of the streamers, and allows a path of about 15 cm for the 5.5 MeV alpha particles used. Mixtures of argon and TEA were also found to be adequate for streamer operation. However, the introduction of other organic quenchers such as methane makes the triggering of the streamers difficult, thus necessitating a higher proportional gain in the first gap, which was undesirable for this application.

For most of the results described below, the primary charge was deposited in the drift space by a collimated beam of 5.5 MeV alpha particles from a ^{241}Am source, nearly parallel to the plates and perpendicular to the direction of the wires within $\pm 20^\circ$. A primary charge estimated at 1.8×10^5 electrons was liberated.

3. THE PROPORTIONAL-TO-STREAMER TRANSITION

In fig. 2 the currents from the first-gap cathode and from the second-gap anode (attenuated) were summed electronically to give a global view of the amplification process. The primary charge was deposited by an alpha particle, as stated above. Figure 2a shows the case of proportional operation: after a preamplification in the first gap (negative peak) the charges drift to the second gap (negative plateau), where they are further amplified (positive peak) and collected in the anode. With a further increase in the second gap's gain, the proportional-to-streamer transition is observed (fig. 2b). Shortly after the arrival and amplification of the charges at the second gap, there is a fast and large increase in the current, corresponding to a pre-breakdown condition. This short delay between the proportional signal and the pre-breakdown signal is characteristic of breakdown in quenched gases (see Raether [7]), which is interpreted by the 'streamer theory' [7, 11].

Once the streamer establishes a conductive channel between the anode and the cathode, the discharge goes through several phases [12], eventually ending in a spark. With our segmented anode the visual aspect of the discharge is diffuse, with a cathode

spot being sometimes visible, but the filamentary stage is not reached. These discharges are visually similar to the ones presented in ref. [13].

4. STREAMER OPERATION OF THE PARALLEL-PLATE CHAMBER

The operational behaviour of the MSAC in streamer mode is illustrated in fig. 3. The current signal was collected from the cathode of the second gap and amplified by a $50 \mu\text{s}$ time-constant integrator, yielding a pulse proportional to the total signal charge. A current pulse fed to the amplifier input in parallel with the chamber signal provided absolute charge calibration. A discrimination level was set in such a way that the background counting rate was a fraction of a hertz, but the proportional signal from the alpha particles was easily detected. The output of this discriminator provides the 'total counting rate'. Another discriminator was set at a high voltage level so that it was never triggered by the proportional signal but was always triggered by any discharge, thus providing the 'streamer counting rate'. The output of both discriminators was counted during 100 s for all the data points.

In fig. 3a the total counting rate (open symbols) and the streamer counting rate (solid symbols) are represented as a function of the second gap voltage with the first gap gains at 1 (squares) and 10^3 (triangles). The background contribution is negligible for all curves. The corresponding total charge and gain are plotted in fig. 3b. The gain is calculated as the total charge collected at the final anode, divided by the primary charge.

For a gain of 1 in the first gap (open squares), corresponding to single-step operation, there is a plateau for proportional signals from gain 10 onwards, owing to the very high primary charge deposition. The proportional gain is limited to about 10^4 by the appearance of spurious signals and sometimes low-current, stable, permanent discharges. It is only near this limit that a sizeable fraction of the alpha particles will cross the streamer threshold (solid squares). Because the energy deposition is higher at the end of the track, the triggering of streamers always starts there, and a further increase in gain is required in order to reach an homogeneous luminosity along the track. A single-gap configuration seems to be inadequate for producing good quality tracks.

When the device is operated in multistep mode, the more favourable operation point is when most of the gain is provided by the first gap ($\sim 10^3$). The reduced gain in the second gap allows more stable operation, with less spurious signals and no permanent discharges. The streamer threshold is crossed at a total proportional gain (fig. 3b, triangles) of 10^4 (corresponding to a gain of 10 in the second gap), and the gain quickly jumps by 3 orders of magnitude (to about 10^7) with the appearance of the

streamers. The corresponding increase in the streamer rate can be seen in fig. 3a (solid triangles). There is now a streamer plateau where the full tracks are visible and the detection efficiency in streamer mode is near 100%. These tracks can be seen without difficulty by the naked eye in a darkened room, but they are not bright enough to be detected by low-noise CCD cameras with enough S/N ratio for a good quality image.

The voltage drop on individual wires during a discharge is around 900 V, and with a total capacity per wire (gap + printed circuit + connectors) of 1 pF, the RC recovery time is 100 μ s. This time can be decreased by reducing the current-limiting resistors. The light emission and current signal from the discharges are of a few microseconds duration.

Radiation other than alpha particles can be detected in the streamer mode. In fact, both the conversion of X-rays by photoelectric effect and the Compton scattering of γ -rays produce low-energy electrons, which can ionize the gas at a charge density that is comparable with the alpha tracks. Soft X-rays are easily detectable, and electron tracks from the natural γ background are frequently visible. However, minimum-ionizing particles (MIPs) could not be detected. In high proportional gains, which are necessary to get the MIPs' low ionization density tracks to cross the streamer threshold, the X and γ background saturates the chamber and spurious signals start to appear, causing excessively high currents to flow across the streamer gap. This difficulty can, in principle, be overcome by gating the chamber upon an external trigger.

5. FURTHER ENHANCEMENTS TO THE CHARGE GAIN AND LIGHT YIELD

Once the streamer establishes a conductive channel between the anode and the cathode, the characteristics of the subsequent discharge are largely dependent on the external circuit. The energy available for the discharge depends on the capacitance associated with each wire, since the very high current-limiting resistors cannot supply a significant amount of charge during the few microseconds duration of the discharge. In fact if these resistors were to permit enough current to maintain the discharge, then a permanent discharge would appear.

If each wire is equipped with external supplementary capacitors (decoupling them to the ground), then the available energy will increase and the charge and light gain will be enhanced. Figure 4a shows the effect of such capacitors (one per wire) on the total charge produced from an alpha-particle track (15 cm long). The first point corresponds to the initial capacity of the wires and associated chamber hardware (about 1 pF). The charge signal is linear with the capacitance, up to the highest capacitance tried, i.e. 57 pF, corresponding to a charge of 7.4 μ C per track. This value was $\sim$ 50 times higher

than the charge collected without external capacitors. Considering the factor of 700 already gained in the proportional-to-streamer transition, a total gain enhancement of 3×10^4 was achieved above the maximum proportional gain. The absolute charge gain in streamer mode is then 3×10^8 .

Figure 4b shows the light-to-charge ratio, as a function of the wire capacitance, for streamer operation. The light yield grows more slowly than the charge; for 57 pF of added capacity, there is a departure from linearity by a factor of 2. For our Microcosm exhibition chamber, we chose an external capacitance of 15 pF (second point), which provided enough light for the tracks to be detected by a low-noise CCD camera.

With a charge per track that is 10^4 times higher than in proportional mode, ageing is a potential problem. It shows up as hair-like growths on the anode wires, as etching and material deposition on the cathode wires, and as deposits over the wavelength-shifter foil of an unknown substance that prevents the UV light from reaching the converter, thus greatly decreasing the light yield. In fact it is this last effect that most severely limits the chamber lifetime. A test with 57 pF capacitors points to a maximum charge deposition in the gap of about 0.3 C/cm^2 , but this value should be taken as order of magnitude only. It corresponds to a lifetime of about 1000 hours of working time for the Microcosm configuration. The original performances can be restored by disassembling the chamber and cleaning the meshes and wavelength shifter.

6. IMAGING OF ALPHA PARTICLES

This section describes the chamber characteristics for the imaging of alpha tracks in streamer mode. The alpha particles were introduced into the chamber as described in section 2. The chamber was equipped with 15 pF capacitors on the last anode wires and filled with the gas mixture (He+TEA) described above. The event rate was around 2 Hz.

The total charge spectrum can be seen in fig. 5. It has an asymmetric shape, with a sharp cut-off on the high-charge side and a tail on the lower side. Ideally, every wire along the track's projection should discharge and contribute by an equal amount to the charge in the total signal, resulting in a sharp peak at the maximum available charge (stored previously on the capacitors). Most frequently, not all the wires along the track will discharge, owing to the statistical nature of charge multiplication and streamer triggering, which cause a tail to appear in the lower part of the spectrum. Also, because of the inclination of $\pm 20^\circ$ of the alpha particles (see section 2), the number of wires triggered for every track is variable, resulting in some signal fluctuation. If the proportional gain is insufficient, then many wires will not discharge and the tracks will

be segmented, incomplete, or dim. Thus the peak will move to the lower side of the charge spectrum, away from the maximum charge limit. This charge spectrum is used by the chamber control system in the Microcosm exhibition to estimate the quality of the tracks and adjust the chamber gain accordingly. In fig. 5 most of the tracks are near the limit, implying that most of the available energy was used, yielding tracks that are bright and homogeneous along their length. There is some contribution from highly ionizing cosmic rays in the lower part of the spectrum.

The light distribution along the track's length is represented in fig. 6a for a single track, randomly selected. Near the end of the track the luminosity is slightly higher, probably because of an increased triggering efficiency caused by the higher primary charge density.

The track width distribution can be seen in fig. 6b. This distribution was calculated from the r.m.s. widths of 400 track samples at different heights in the chamber, for 40 different tracks. The average r.m.s. track width is 2 mm, and it varies by 47% FWHM along the track's length. This width is understandable when we consider that the UV light emitted by the discharges is proximity-focused onto the wavelength shifter (placed near the anode), and—unlike the proportional case—the light is emitted over the full anode-cathode space of 5 mm.

The visual appearance of the tracks can be seen in fig. 7, where the images of four tracks, recorded by the CCD camera, were superimposed. The dimensions are $20 \times 15 \text{ cm}^2$.

7. CONCLUSIONS

We have demonstrated the possibility to operate the imaging chamber in a non-proportional mode, with charge and light gains in excess of 10^4 over the proportional operation. The device is not pulsed, and the main limitations are the existence of a detection threshold that is dependent on the primary charge density, and the recovery time after an event ($\sim 100 \mu\text{s}$). The amount of current flowing across the high-gain gap leads to ageing and rate limitation. The device is also completely free of sparks, and the same principle can be used to spark-protect MSACs operating in proportional mode.

Alpha particles and soft X-rays can be detected in streamer mode, but we failed to detect MIPs owing to the natural X-ray background, which caused an excessively large event rate. Stopping electrons, with a few centimetres path length, from Compton scattering of γ -rays were also visible.

A device of this type was installed at Microcosm, the permanent CERN exhibition for the general public, displaying alpha tracks 15 cm long (in He+TEA gas). The tracks

can be easily seen by the naked eye in a moderately lit room, and are also imaged by a CCD camera and displayed on a screen after digital treatment (colour coding, etc).

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REFERENCES

- [1] G. Charpak and F. Sauli, Phys. Lett. **78B** (1978) 523.
- [2] R.S. Gilmore et al., Nucl. Instrum. Methods **206** (1983) 189.
- [3] D.M. Potter, Nucl. Instrum. Methods **228** (1984) 56.
- [4] T.K. Gooch et al., Nucl. Instrum. Methods **A241** (1985) 363.
- [5] G. Charpak et al., Nucl. Instrum. Methods **A258** (1987) 177.
- [6] G. Charpak et al., IEEE Trans. Nucl. Sci. **NS-35** (1988) 483.
- [7] H. Raether, Electron avalanches and breakdown in gases (Butterworth and Co. Ltd., London, 1964).
- [8] C. Gruhn, Z. Natkaniec, A. Peisert and F. Sauli, Nucl. Instrum. Methods **A247** (1986) 460.
- [9] M. Suzuki et al., Nucl. Instrum. Methods **A254** (1987) 556.
- [10] V. Peskov, G. Charpak, W. Dominik and F. Sauli, Nucl. Instrum. Methods **A277** (1989) 547.
- [11] E.D. Lozanskii, Development of electron avalanches and streamers, Sov. Phys.-Usp. **18** (1976) 893.
- [12] S.C. Haydon, Spark channels, *in* Electrical breakdown of gases, ed. J.A. Rees (The MacMillan Press, Ltd., London, 1973), p. 146.
- [13] G. Charpak, A. Breskin and F. Piuz, Nucl. Instrum. Methods **100** (1972) 157.

Figure captions

Fig. 1: Schematic view of the device.

Fig. 2: Summed current signals from the first-gap cathode and second-gap anode (inverted polarity). a) Proportional operation. b) Streamer operation.

Fig. 3: Rate and gain curves. a) The total (open symbols) and streamer (solid symbols) counting rates as a function of the second-gap voltage, with first-gap gains of 1 (squares) and 10^3 (triangles). b) Total charge gain as a function of the second-gap voltage, with first-gap gains of 1 (squares) and 10^3 (triangles).

Fig. 4: a) Total charge per alpha track as a function of the external capacitors. b) Light-to-charge ratio as a function of the external capacitors.

Fig. 5: Total charge per alpha-track distribution for streamer operation. The peaked part has a 22% FWHM.

Fig. 6: a) Light distribution along the track's length for a single track. b) r.m.s. track-width distribution: the average width is 2 mm with a variation of 47% FWHM.

Fig. 7: Images of the alpha-particle tracks; dimensions $20 \times 15 \text{ cm}^2$.

Fig. 1

Fig. 2

Fig. 4

Fig. 3

Fig. 5

Fig. 6

Fig. 7