The CsI Multi-GEM Photomultiplier

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Abstract
We describe the properties of a gas-avalanche photomuliplier, combining a CsI photocathode and a cascade of 3 or 4 GEM electron multipliers. The detector is filled with argon and other non-aging mixtures of Ar/Ne , Ar/Xe , Ar/N_2 and with Ar/CH_4 , at atmospheric pressure.
Very high gains, above 10^5, and fast anode pulses, down to 10 ns, were observed in some of the gas mixtures. We summarize the main results and the principal advantages of the multi-GEM photomultiplier. Future prospects, including the possible application to visible light imaging, are discussed.

1. Introduction

Gas avalanche photomultipliers [1], combining solid photocathodes and fast electron mulipliers, provide an attractive solution for photon localization over very large sensitive areas and under high illumination flux. They offer single photon sensitivity and the possibility of operation under intense magnetic fields.

In such photomultipliers, photoelectrons are emitted from the photocathode into a gas. Depending on the type of electron multiplier coupled to the photocathode and on the electric field at the photocathode surface, they either drift to the multiplying electrode or experience a multiplication process at their emission location. In both cases, the surface photo-conversion, followed by surface emission, make these detectors very fast and insensitive to the radiation incidence angle [2].

Unlike vacuum devices, these detectors can operate in high magnetic fields [3]. The operation under atmospheric gas-pressure permits the construction of large area, thin, flat detectors of sizes limited mainly by the photocathode production technology. Highly integrated readout electronics, developed for particle physics applications, permits the conception of highly pixelized position sensitive photon detectors, capable of operation at high photon flux and under MHz frame rates.

The photon detection efficiency of these gas avalanche photomultipliers, over a given spectral range, depends on three factors: the photocathode quantum efficiency (QE), electron back-scattering from the photocathode into the gas [4] and the efficiency of detecting single electrons with the gas multiplier. The latter depends on the multiplier gain, its signal shape (which is multiplication mechanism-dependant) and on the readout electronics (integration time, noise).

The long-term stability depends principally on the photocathode, which may be degraded either by chemical reaction with gas impurities or by accumulated impact of photons and avalanche-originated ions. UV-photocathodes of CsI [5], CsBr [6] and CVD-diamond films [7] are relatively chemically stable, while visible-range photocathodes can be protected by coating them with thin alkali-halide (CsI, CsBr) films [8].

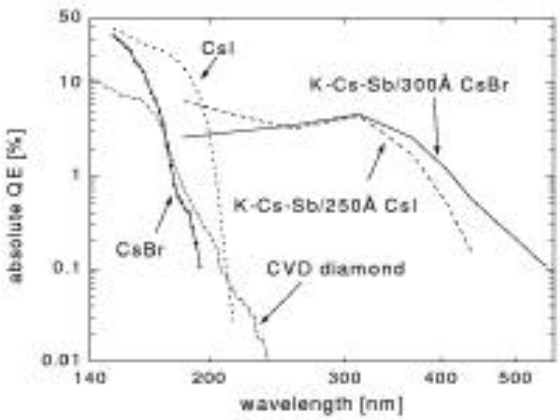

Fig. 1. Typical values of absolute quantum efficiency in the UV and visible range for alkali-antimonide, diamond and protected K-Cs-Sb photocathodes.

Typical values of the quantum efficiency (QE) of UV- and protected alkali-antimonide visible-photocathodes are shown in Fig.1. Large-area (square meters) CsI-based wire chambers are currently employed or under construction for UV-photon localization in Cherenkov Ring Imaging (RICH) detectors, in numerous particle physics experiments [3,9].

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The operation in high-purity gases, particularly in non-aging mixtures of noble gases, could be of considerable advantage for photomultipliers equipped with visible-light photocathodes. However, detectors with noble gas mixtures have not been employed for single photon detection, the gain being limited by photon-feedback effects. Aging of the photocathode due to ion impact [5] is also a concern; it can be considerably reduced by a proper choice of the electron multiplier, the gas mixture and the operation conditions, as discussed below.

The type of electron multiplier coupled to the photocathode could play a decisive role. On one hand, it should provide high gas amplification for enhanced single-photon sensitivity; on the other hand, its operation mode should prevent an accelerated degradation of the photocathode and limit its exposure to avalanche-generated photon- and ion-feedback effects. A comprehensive discussion on potential electron multipliers for gas avalanche photomultipliers, is given in Ref. 1.

The recently introduced GEM [10,11] could particularly suit our application, due to its very special electrode geometry [12]. This simple multiplier consists of a compact array of small apertures in a double-sided metal-coated, 50 micron thick, Kapton foil. The apertures, of 30-100 microns in diameter, are typically spaced by 150-200 microns. A potential difference of a few hundred volts across the GEM foil, leads to avalanche formation within the apertures, reaching amplification factors above 1000 in a single element, both at atmospheric [10,11] and low [13,14] gas pressures. Very high gains, exceeding 10^5, and stable operation have been reached by cascading a GEM with MWPC or MSGC multiplying elements [10,11,13].

The GEM inserted in a gas avalanche photodetector, between the photocathode and the following multiplication elements, plays a multiple role:

- It transmits photoelectrons into the multipliers, while screening the photocathode from avalanche feedback photons as demonstrated in Ref.13.
- In some electric field configurations, the GEM would block a fraction of the back-drifting ions.
- Some gain on the GEM permits reducing the gain on the following multiplication elements, leading to more stable operation. It allows for higher total gain and therefore higher sensitivity to single photons.
- The thin GEM electrode permits for very fast avalanche mechanism, leading to fast signals [13] and therefore good time resolution.
- The deposition of a photocathode on top of the GEM surface [13] should permit an operation free of photon feedback effects.

The recent demonstration that high multiplication factors could be reached in a single GEM element operated in pure argon [15] could be considered as a breakthrough in the field of detectors. The high gain

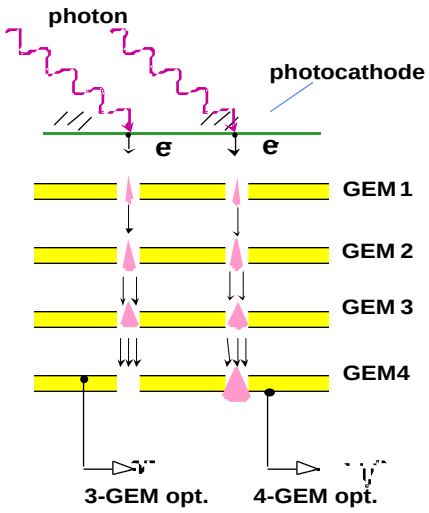

Fig. 2. A multi-GEM photomultiplier consisting of 4 consecutive GEMs. A photon-induced electron is emitted from a solid photocathode. Avalanche multiplication takes place in the GEM holes, with each GEM operating at a low gain. The resulting avalance induced pulses can be read out either on the top or bottom electrode of the last GEM, in a 3-GEM operation mode or a 4-GEM operation mode.

is due to the confinement of the avalanche within the thin GEM apertures [16], limiting the photon-mediated avalanche growth. The possibilty of operation in noble gases has led to the conception of high gain, multi-GEM amplification structure, particularly suited for gas avalanche photomultipliers. The almost complete elimination of photon-feedback effects in such structures, permits, for the first time, reaching very high gains (> 10^5) in noble gas mixtures [17,18]. This should allow safe operation with sensitive alkali-antimonide visible photocathodes.

2. The multi-GEM photomultiplier

The basic concept of the multi-GEM photomultiplier, its operation mechanism and properties are described in length in some recent publications [17-19]. We will therefore summarize very briefly the most important and significant points.

The detector investigated, shown in Fig.2, comprises a cascade of four GEM elements coupled to a semi-tranparent CsI UV-photocathode. The first 3 GEMs have a double-conical hole shape, of 80 micrometer in diameter on the metal electrodes, arranged in a hexagonal lattice with 140 micrometer pitch. The first and third GEMs have very narrow holes in the Kapton, of 30 micrometers only, for efficient screening against photon-feedback. The fourth GEM has cylindrical holes, 80 micrometer in diameter, arranged in a square lattice of 200 micrometers.

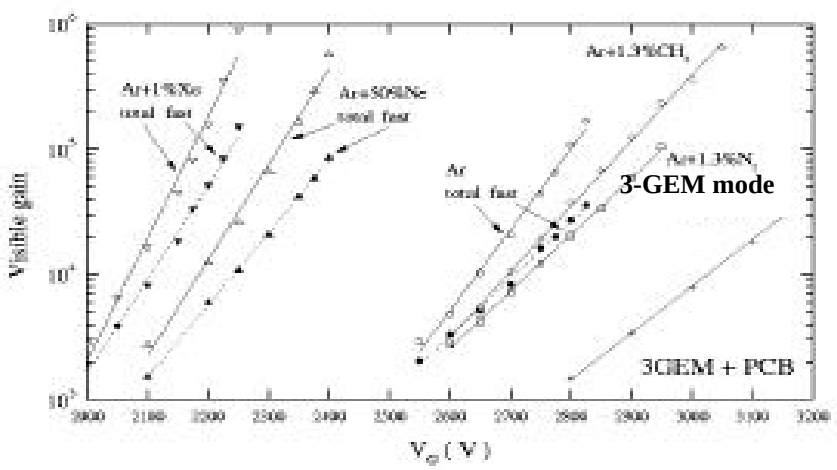

Fig. 3. Gain-voltage characteristics of a 3-GEM photomultiplier in different gas mixtures. For the mixtures having secondary scintilation effects in the photocathode gap, the contribution of the fast (primary) component is also shown.

The first three GEMs are polarized by a voltage divider, described in Ref. 17. In a 3-GEM operation mode, the upper surface of GEM 4 acts as a readout electrode: it can either measure an amplified current or pulses, when connected to proper amplifiers. In a 4-GEM operation mode, the information is read out from the last (lower GEM 4) electrode. Typical electric fields, in the case of argon, were 1.3 and 2 kV/cm, in the photocathode- to-GEM 1 gap and between the GEMs, respectively.
The multi-GEM photomultiplier was operated with the following non-aging gases and mixtures: Ar, Ne, Ar/Ne, Ar/Xe and Ar/N_2 and with Ar/CH_4.

3. Principal results

Some gain curves in the 3-GEM operation mode are shown in Fig.3. The Ar/Xe, Ar/Ne and Ar/CH4 mixtures were chosen so as to reduce gain limitions due to ion-induced electron emission from the GEM electrodes [17,18]. Such ion-feedback effects [13], observed here in argon, could be suppressed either by exchanging Ar ions for those of CH_4, reducing the electron emission cross section, or by a decrease of ion energy with the Xe and Ne additives. The reduction of ion velocity is due to the considerably lower operation voltages, as shown in Fig.3. The physical mechanisms are explained in detail in Refs.17,18.

Photon-feedback effects in these noble gas mixtures are due, to a large extent, to gas-scintillation. The most relevant, in our case, are photon emission during the drift of the photoelectron from the photocathode to the first GEM and photon emission originating from the avalanche within the holes of the first GEM. Avalanche-induced photons from any other GEM are mostly absorbed by the preceding ones. Indeed one could use the first GEM as a screen only, at gain 1.

The scintillation process enlarges the electrical pulses, both in time and in height. This effect is reflected in the "total" versus "fast" amplification curves shown in Fig.3. One can remark that the slow scintillation-induced "gain enhancement" reaches values of 2-10, yielding "gains" of the order of $5x10^5$. However, the useful, fast component of the pulse, corresponds to gains of the order of 10^5 in Ar/Ne and Ar/Xe.

It should be noted that this photon-induced phenomenon is absent in non-scintillation mixtures, e.g. in Ar/CH_4 and Ar/N_2, where the gain is about $8x10^5$ and 10^5, respectively. The difference in pulse- shape between scintillating and non-scintillating mixtures is shown in Fig.4. The non-scintillating mixtures also provide a fast response; the pulse-width in $Ar+10\%CH_4$ is of 22 ns and in $Ar+10\%N_2$ it is as short as 11 ns (Fig.5). By comparison, the pulses in Ar/Ne and Ar/Xe mixtures are 80-110 ns wide [17].

The best mixture from the point of view of single photon detection was found to be Ar/CH_4, in which we observed pulse saturation [17-19].

The operation in the 4-GEM mode did not provide any additional advantage comapred to the 3-GEM one described above. The pulses recorded in the 4-GEM mode are higher, but they comprise a small, fast electron component followed by a larger, slow ion component (see fig.6). The latter is absent in the 3-GEM device, in which only the electron component was read out on the upper face of GEM 4 (serving as a readout electrode). The fact that the 4-GEM structure did not yield any higher gain, could indicate that the maximal amplification reached in such devices, with noble gas mixtures, is somewhat limited by space-charge effects.

Other topics, related to the operation mechanism of multi-GEM structures, are discussed in detail in Refs. 17-19.

4. Summary

The multi-GEM photomultiplier could become an instrument of choice for fast photon imaging, down to the single photon level. The newly opened possibiltiy of reaching high multiplication factors, above 10^5, in noble gas mixtures, could pave the way towards large-area

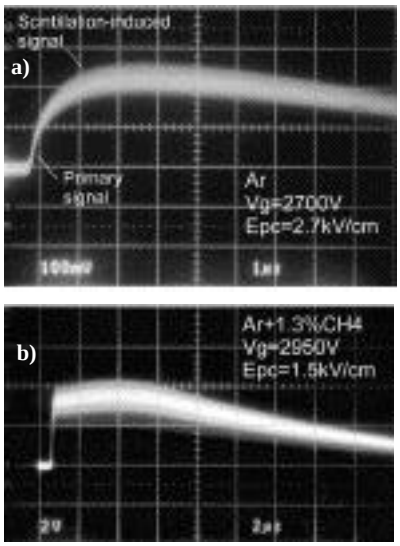

Fig. 4. Charge pulses obtained from the 3-GEM photomultiplier for (a) Argon, where secondary scintilation can be seen and for (b) a poorly scintilating mixture (Ar+1.3% CH_4)

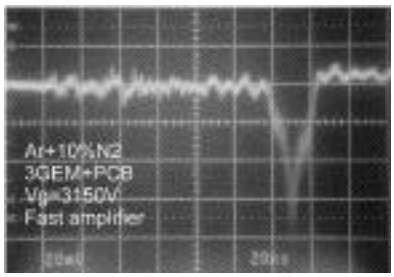

Fig. 5. Anode signals detected with a fast amplifier from the 3-GEM detector, operating in Ar+10% N_2. The signal results from 90 primary electrtons emitted from the photocathode

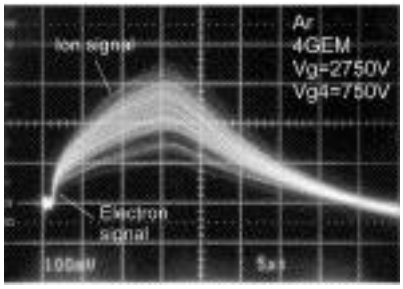

Fig. 6. Ion-induced charge signals in a 4-GEM photomultiplier, operating in Ar.

imaging devices for visible light. With high purity detector materials, e.g. metal/ceramic or metal/glass [20,21] technologies, one could in principle employ bare alkali-antimonide photocathodes in pure noble gas mixtures.

As discussed in ref.17, one gets full electron extraction efficiency into the noble gas mixture, provided the field at the photocathode surface is sufficiently high. The remaining problem is in preserving the QE of the photocathode, namely, making sure that for each emitted photoelectron from the photocathode one gets a signal from the photomultiplier. As the collection efficiency of the first GEM is not 100%, it was proposed [12-14] to slighly preamplify the emitted photoelectron, by a factor of 2-6; this would guarantee that at least one electron initiates an avalanche within the first GEM. The gain of the first GEM should be kept low, to prevent secondary-photon effects on the photocathode. The important issues of single-electron detection efficiency, absolute quantum efficiency of GEM-based photomultpliers with photocathodes deposited on the GEM face, and photocathode aging studies, are subject to intensive investigations.

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