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Efficient ion blocking in gaseous detectors and its application to gas-avalanche photomultipliers sensitive in the visible-light range

A. Lyashenko [a,*], A. Breskin [a], R. Chechik [a], J.M.F. dos Santos [b], F.D. Amaro [b], J.F.C.A. Veloso [b,c]

[a] Department of Particle Physics, The Weizmann Institute of Science, 76100 Rehovot, Israel
[b] Physics Department, University of Coimbra, 3004-516 Coimbra, Portugal
[c] Physics Department, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

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ABSTRACT

A novel concept for ion blocking in gas-avalanche detectors was developed, comprising cascaded micro-hole electron multipliers with patterned electrodes for ion defocusing. This leads to ion blocking at the 10^{-4} level, in DC mode, in operation conditions adequate for TPCs and for gaseous photomultipliers. The concept was validated in a cascaded visible-sensitive gas-avalanche photomultiplier operating at atmospheric pressure of Ar/CH_4 (95/5) with a bi-alkali photocathode. While in previous works high gain, in excess of 10^5, was reached only in a pulse-gated cascaded-GEM gaseous photomultiplier, the present device yielded, for the first time, similar gain in DC mode. We describe shortly the physical processes involved in the charge transport within gaseous photomultipliers and the ion blocking method. We present results of ion back-flow fraction and of electron multiplication in cascaded patterned-electrode gaseous photomultiplier with K–Cs–Sb, Na–K–Sb and Cs–Sb visible-sensitive photocathodes, operated in DC mode.

1. Introduction

Controlling the back-flow of ions generated in gas avalanches has important consequences on the operation and properties of gaseous detectors. Avalanche ions induce space charge effects that limit the gain, counting-rate capability and localization properties of tracking detectors. The ion impact on photocathodes (PCs) of gaseous photomultipliers (GPM) causes their permanent damage [1,2]; more seriously, it induces the emission of secondary electrons which, in turn, cause avalanche divergence, deterioration of timing and localization information and, most importantly, severe gain limits. All these consequences are included in the term ion feedback effects. GPMs sensitive in the UV range, with CsI PCs, do suffer some ion-induced PC damage [2], but the ion-induced secondary electron emission probability is very low and does not limit their operation, even at high gain. There are numerous large-area CsI-GPMs, presently operating or under construction, in many particle-physics experiments, e.g. COMPASS [3] and ALICE [4] at CERN and PHENIX [5] at BNL.

The ion feedback effects are particularly problematic in visible-sensitive GPMs, due to the high electron emission probability of bi-alkali and other PCs sensitive in the visible spectral range. The reader is referred to Ref. [6] for an extended discussion on this subject and references to recent works dealing with methods of ion back-flow (IBF) reduction.

The only method for significantly reducing the IBF fraction and reaching high-gain operation in visible-sensitive GPMs has been, so far, their operation in a gated mode [1]. Our goal has been to find methods for efficiently reducing the IBF to permit the operation of visible-sensitive GPMs in DC mode with single-photon sensitivity. Obviously, large tracking TPCs will also benefit, as low IBF values would permit their stable DC operation.

In the present article, we report on our recent results on blocking of IBF in cascaded micro-hole multipliers comprising GEMs and other patterned electrodes. We discuss the ion-induced secondary electron emission and provide solutions that permit, for the first time, the operation of visible-sensitive GPMs in DC mode, with gain of 10^5.

2. Requirements for stable operation of visible-sensitive GPMs

2.1. General consideration on IBF and ion feedback effects

While cascaded micro-hole multipliers, with their significant optical "opacity", efficiently block avalanche-photon feedback [7], they are less efficient in blocking the back-flow of avalanche ions. The latter, originating from each avalanche stage in the cascaded multiplier, drift back to the GPMs' PC following the device field lines, and a major fraction of them follow the same paths

* Corresponding author: Tel.: +972 8 934 2064; fax: +972 8 934 2611.
E-mail address: alexey.lyashenko@weizmann.ac.il (A. Lyashenko).

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(in opposite direction) of the initial photoelectrons and their successive avalanche electrons [6]. When impinging on the PC's surface they release secondary electrons; the latter initiate secondary avalanches, known as ion-feedback, which, by positive feedback mechanism diverge the proportional avalanche multiplication into discharge [8]. An example of ion-feedback effect measured in a double-GEM multiplier with K–Cs–Sb visible-sensitive PC operating in Ar/CH_4 (95/5) at 700 Torr (Fig. 1a), is the deviation of the gain–voltage curve from exponential (Fig. 1b). The measured gain, G_{meas}, contains contributions from ion feedback and is described by

$$G_{meas} = \frac{G}{1 - \gamma_+ \cdot \mathrm{IBF} \cdot \varepsilon_{extr} \cdot G}, \quad (1)$$

where γ_+ is the *ion-induced secondary emission probability* or the ion feedback probability, IBF is the ion back-flow fraction namely the fraction of ions, from all avalanche stages of the multiplier, flowing back to the PC (or to the drift region of a tracking detector), ε_{extr} is the efficiency of extracting secondary electrons from the PC into the gas and G is the multiplier's gain without ion feedback. To avoid avalanche divergence into a spark, the above formula should fulfill $\gamma_+ \cdot \mathrm{IBF} \cdot \varepsilon_{extr} \cdot G < 1$. Therefore, a gain of 10^5, required for good single-photon sensitivity in GPMs, implies $\gamma_+ \cdot \mathrm{IBF} \cdot \varepsilon_{extr} < 10^{-5}$.

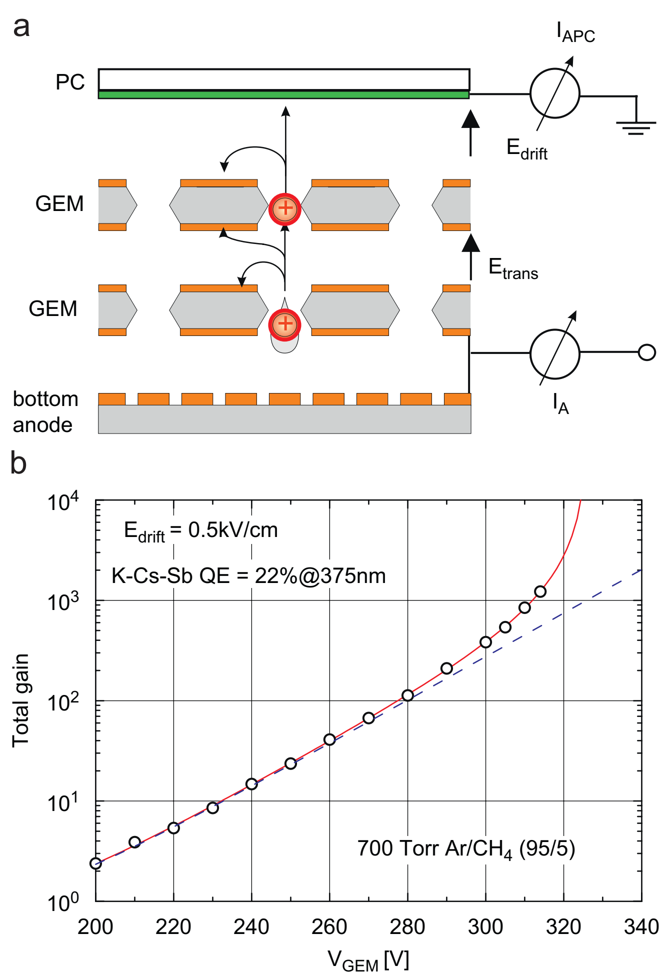

Fig. 1. (a) A double-GEM GPM coupled to a semitransparent photocathode; (b) gain–voltage characteristics measured in this GPM (see conditions in the figure, QE refers to vacuum) with CsI (dashed) and K–Cs–Sb (open circles) photocathodes. The divergence from exponential with K–Cs–Sb is due to ion feedback.

2.2. Measurement of γ_+ and ε_{extr}

The extraction efficiency ε_{extr} of secondary electrons is the fraction of electrons emitted from the PC and not scattered back (by collisions with gas molecules) into it [9,10]. ε_{extr} depends on the kinetic energy distribution of the electrons leaving the PC, which has not yet been measured. The theoretical calculations of energy distribution and extraction efficiency ε_{extr} of ion-induced secondary electrons from PCs are rather complex and differ from those of photon-induced ones [11]. Such calculations are presently under way, in cooperation with T. Dias of Coimbra University, and will be the subject of a future publication.

In the absence of any knowledge of ε_{extr}, we have chosen to use $\gamma_+^{eff} = \gamma_+ \cdot \varepsilon_{extr}$; the latter can be extracted from the experimental GPM's gain curve and its deviation from exponential line. γ_+^{eff} is defined as the effective ion-induced secondary emission probability or the effective ion feedback probability. It was extracted from fitting the experimental gain curve G_{meas} by Eq. (1) (solid line in Fig. 1b). A significant deviation from the exponential gain–voltage characteristic (dashed line in Fig. 1b) is observed with the bi-alkali PC already at low gain. The IBF and G as a function of GEM voltage were measured in the same detector (geometry, gas and voltages), with a CsI PC, ensuring no ion feedback. The drift field between the PC and the top face of the first GEM was kept constant at 0.5 kV/cm throughout the entire measurements. In GPMs it provides about 60% extraction efficiency of photoelectrons in this gas [8]. The gain–voltage characteristics, like the one shown in Fig. 1b, were measured for K–Cs–Sb, Na–K–Sb and Cs–Sb PCs; they yielded γ_+^{eff} values of $\sim 3 \times 10^{-2}$ for all these PCs. This study and the results will be discussed in more detail elsewhere.

2.3. Requirements for IBF

Establishing the effective ion feedback value γ_+^{eff} with the visible-sensitive PCs under investigation, we can set the limits on the IBF value needed for stable DC operation of visible-sensitive GPMs at a gain of 10^5. Requiring $\gamma_+^{eff} \cdot \mathrm{IBF} < 10^{-5}$, and using the estimated value $\gamma_+^{eff} = \sim 3 \times 10^{-2}$, the IBF value should be $< 3.3 \times 10^{-4}$.

3. IBF reduction in cascaded micro-hole multiplier structures

A straightforward way to reduce the IBF is by lowering the drift field, since IBF decreases linearly with the drift field [12]. However, in GPMs the drift field could not be too low because it controls, the photoelectron extraction into the gas; drift field values of the order of 0.5 kV/cm [8] were generally applied in our GPMs filled with Ar/CH_4 (95/5).

A more detailed report on a comprehensive IBF reduction, study, carried out with a variety of cascaded micro-hole multipliers, can be found elsewhere [6]. All GPM detectors investigated had active areas of $30 \times 30\,mm^2$; they were irradiated over a surface of 15 mm in diameter, at photon fluxes of about 10^6 photons/s cm^2. The core outcome of this study is that very low IBF values can be obtained with cascades combining GEMs and other patterned electrodes derived from the Micro-Hole and Strip Plates (MHSP) [13]. The latter comprised GEM-like holes and additional patterned strips on one of their faces, and they were operated in different modes regarding the voltages and orientation schemes [6]: MHSP, reversed-MHSP (R-MHSP) and flipped-reversed-MHSP (F-R-MHSP). These schemes aim at reducing the IBF by diverting the ions and trapping them on the strips patterned on the surface. While the MHSP, placed at the end of the cascade, can divert and trap only part of the ions generated within its own avalanche stage, the other two types of electrodes can divert ions created in successive multiplying elements; therefore their incorporation in the cascade yielded better results. In a cascade comprising F-R-MHSP followed by GEM and MHSP (Fig. 2a), IBF values as low as 3×10^{-4} were recorded [6]; this fulfills our requirement for stable DC operation at a gain of 10^5 with visible-sensitive PCs (see Fig. 2b). We varied the inter-strip voltage on the bottom MHSP, to vary the total gain of the detector.

Following the success of the above study, and with our understanding of the operation mechanism of the MHSP-like electrodes [6], a new patterned micro-hole electrode named Cobra (Fig. 3) was developed with a geometry that is expected to improve the ion divergence away from the holes. It has thin anode electrodes surrounding the holes and creating strong electric field inside the holes (required for charge amplification); the more negatively biased cathode electrodes cover a large fraction of the area for better ion-collection as compared to the F-R-MHSP [6]. The concept of the Cobra electrode has been recently investigated. It was found that when introduced as a first element (with the patterned area pointing towards the PC), preceding two GEMs in

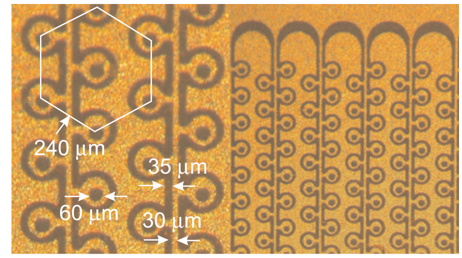

Fig. 3. A microscope photographs of one face of a “Cobra” micro-hole electrode with dimensions given in the figure. The other face is identical to a GEM.

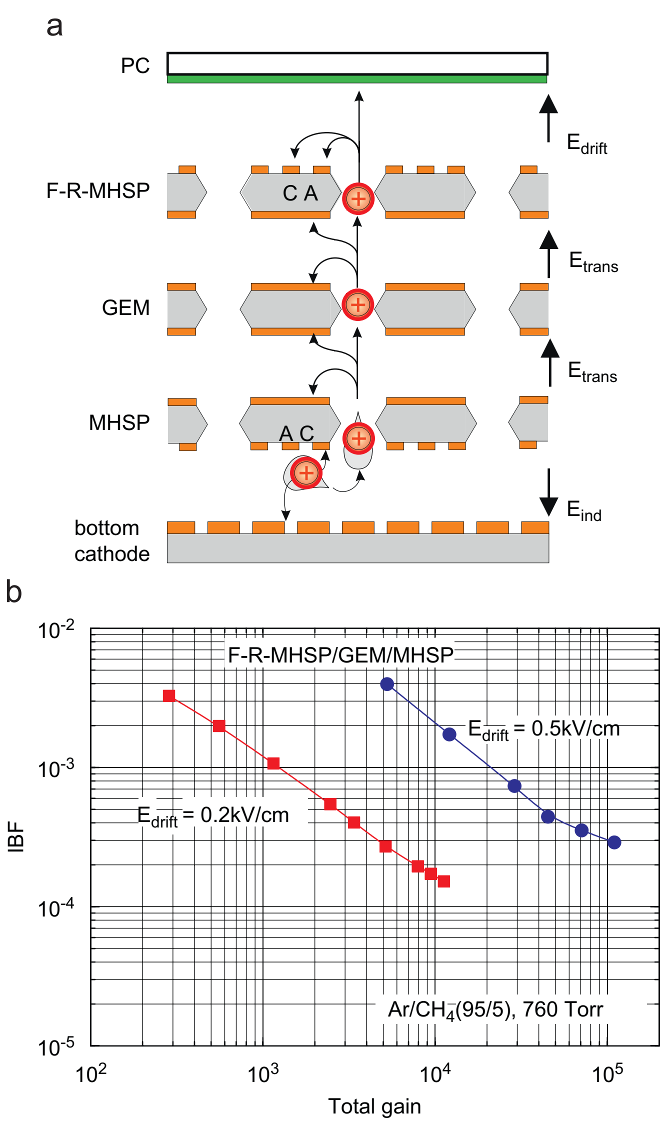

Fig. 2. (a) Scheme of the cascaded F-R-MHSP/GEM/MHSP multiplier coupled to a semitransparent photocathode; possible avalanche-ion paths are shown. (b) The IBF in correlation with the total gain of this GPM plotted for drift fields of 0.2 kV/cm (TPC conditions, squares) and 0.5 kV/cm (GPM conditions, circles).

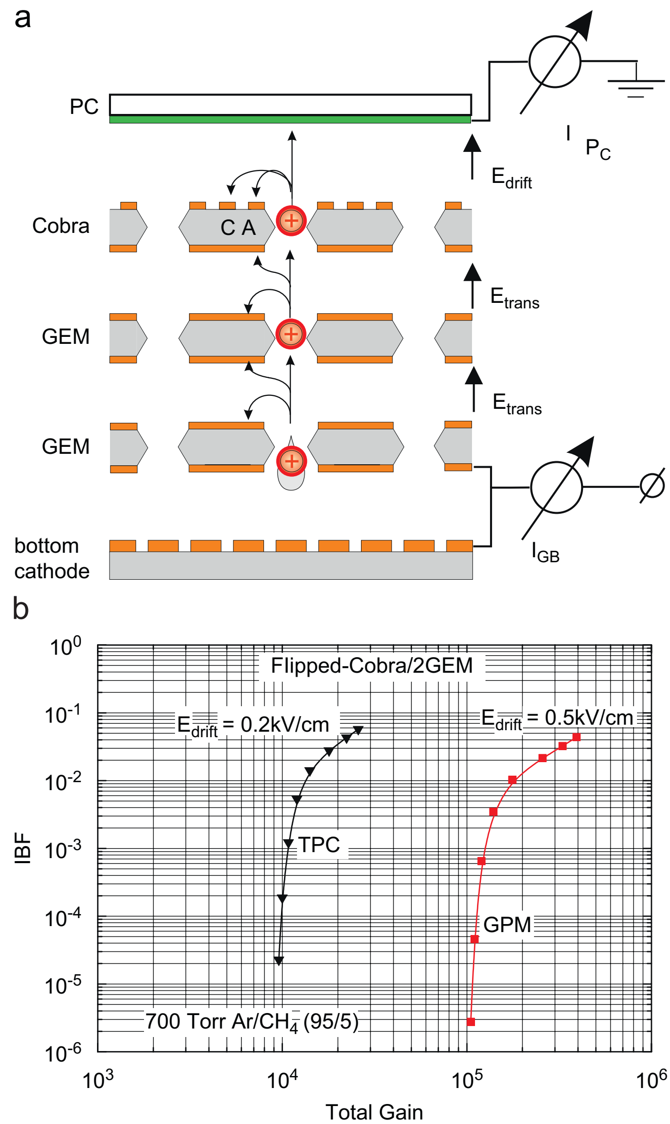

Fig. 4. (a) Scheme of cascaded Cobra/2GEM GPM with a semitransparent photocathode; possible avalanche ion paths are also shown. (b) The IBF as a function of the total gain of the Cobra/2GEM cascaded detector for drift fields of 0.2 kV/cm (TPC conditions, triangles) and 0.5 kV/cm (GPM conditions, squares).

the cascade (Fig. 4a), it drastically improved the ion trapping capability. The IBF as a function of voltage between electrodes on the top surface of Cobra is shown in Fig. 4b. In GPM conditions, with a drift field of 0.5 kV/cm, we measured IBF values of 3×10^{-6} which is 10,000 times lower than that of cascaded triple GEMs. In TPC conditions with a drift field of 0.2 kV/cm the same detector

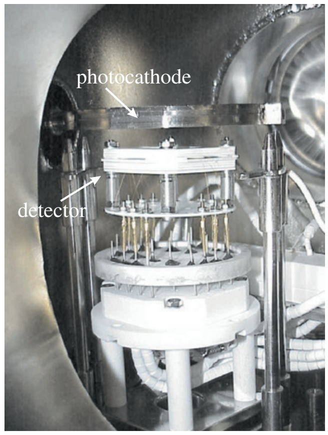

Fig. 5. Photograph of the F-R-MHSP/GEM/MHSP detector and the photocathode, mounted in the vacuum chamber.

configuration provided IBF values as low as 2.7×10^{-5}. These are the lowest IBF values ever reached in gaseous detectors. However, while the F-R-MHSP yielded full photoelectron collection efficiency into the holes of the first cascade element, the Cobra, in its present geometry, had a limited electron collection efficiency of about 20%. This can and should be improved by optimizing the geometrical parameters.

4. DC operation of a visible-sensitive GPM with micro-hole multiplier cascades

The operation of a visible-sensitive GPM in DC mode was investigated with a F-R-MHSP/GEM/MHSP cascaded multiplier, schematically shown in Fig. 2a. A photograph of the experimental detector is shown in Fig. 5. All the multiplier electrodes were mounted between ceramic spacers within a UHV vessel [8]. The PC was prepared and characterized in an adjacent vessel of the dedicated UHV system, and then transported with an UHV manipulator and placed in a stainless-steel holder above the detector. Details can be found in Refs. [8,14]. The K–Cs–Sb PCs had typical quantum efficiency (QE) of 30% measured in vacuum at 375 nm.

The details of the IBF measurements and results for this multiplier configuration were reported in Ref. [6] both in conditions for TPC and for GPM operation (Fig. 2b). Conditions for full efficiency of electron collection from the PC were confirmed and applied in all measurements.

In Fig. 6 we present gain–voltage characteristics for the cascaded GPM of Fig. 2a with a K–Cs–Sb PC and with a CsI PC, for comparison. The measurements were carried out in Ar/CH_4 (95/5) at 700 Torr. The present semitransparent K–Cs–Sb PC had a QE of ~27% measured in vacuum at 375 nm. Its QE value in the gas, with a drift-field of 0.5 kV/cm, was estimated to be 16% [8]. The solid and dashed curves in Fig. 6 represent exponential fits to the data points measured with K–Cs–Sb and CsI PCs, correspondingly. In both cases the GPM could reach a gain of 10^5 with no divergence from an exponential gain–voltage characteristic, indicating upon full suppression of ion feedback effects.

The visible-sensitive GPM with a K–Cs–Sb PC coupled to the Cobra multiplier followed by two GEMs (Fig. 4a) was investigated in DC operation mode; the gain–voltage plots are shown in Fig. 7, in comparison with a CsI PC. The measurements were carried out in Ar/CH_4 (95/5) at 700 Torr. The semitransparent K–Cs–Sb PC had

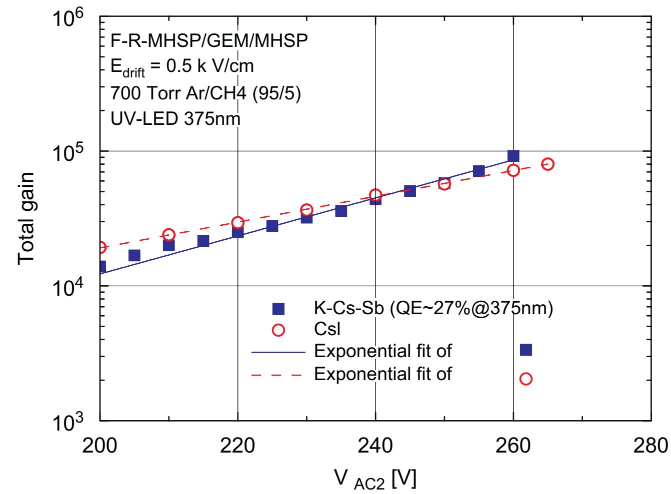

Fig. 6. Gain–voltage characteristics of the detector shown in Fig. 2a with a K–Cs–Sb (squares) and CsI (circles) photocathodes. The data were fitted with exponential functions; no divergence from exponential was observed. Seven hundred Torr Ar/CH_4 (95/5); $E_{drift} = 0.5$ kV/cm. QE refers to vacuum.

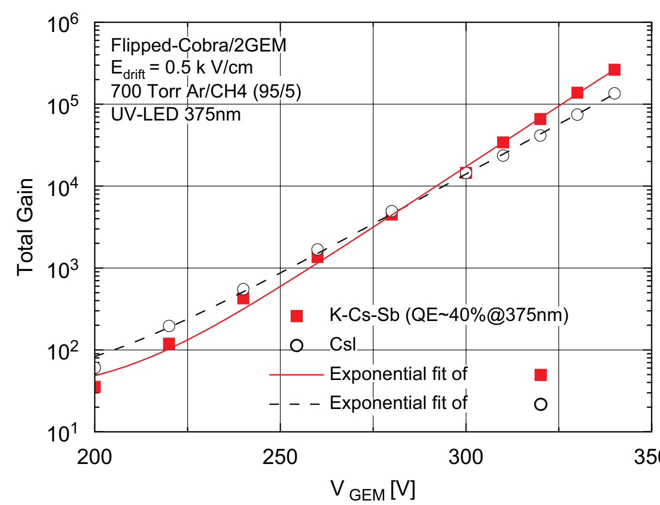

Fig. 7. Gain–voltage characteristics of the Cobra/2GEM cascaded GPM of Fig. 4a, with K–Cs–Sb (squares) and CsI (circles) photocathodes. The data were fitted with exponential functions. 700 Torr Ar/CH_4 (95/5); $E_{drift} = 0.5$ kV/cm. QE refers to vacuum.

~40% QE measured in vacuum at 375 nm. The exponential fits to the data points measured with K–Cs–Sb and CsI PC are represented by solid and dashed curves, correspondingly. There were no feedback effects as can be seen from the exponential shape of the gain–voltage curve.

5. Conclusions

Ion feedback in cascaded micro-hole gaseous detectors was studied with a variety of cascade elements and PCs, in conditions of TPC and of GPM operation. The effective ion feedback probability γ_{+}^{eff} was measured in Ar/CH_4 (95/5) at 700 Torr and found to be 3×10^{-2} for Na–K–Sb, K–Cs–Sb and Cs–Sb PCs. Based on these measurements, the ion back-flow fraction (IBF) required for stable DC operation of cascaded visible-sensitive gaseous photomultipliers (GPM) was estimated to be 3.3×10^{-4}.

Systematic ion blocking investigations with various patterned micro-hole cascaded multipliers yielded the required IBF values, at gain of 10^5. The best results were recorded in a cascaded multiplier of a flipped reversed-bias micro-hole and strip plate flowed by a GEM and by a micro-hole and strip plate (F-R-MHSP/GEM/MHSP). This configuration yielded 100 fold lower IBF value than that measured in cascaded GEMs. This permits reaching stable operation conditions both for TPCs and for visible-sensitive GPMs operating in DC mode.

Even lower IBF values, of 3×10^{-6} at a gain of 10^5 and drift field 0.5 kV/cm, were recorded in a cascade comprising a novel "Cobra" micro-hole patterned multiplier, followed by two GEMs. This IBF value is 10,000 times lower than that measured in cascaded GEMs. However, the electron collection efficiency of the present "Cobra" multiplier was only 20%, which requires further optimization of its geometry.

A visible-sensitive GPM with a F-R-MHSP/GEM/MHSP cascaded multiplier and a K–Cs–Sb PC, yielded, for the first time, stable operation at gains of 10^5 in DC mode with full photoelectron collection efficiency and without any noticeable feedback effects. This is a breakthrough in the field of GPMs.

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