Operation principles and properties of the multi-GEM gaseous photomultiplier with reflective photocathode

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Abstract

Gas Electron Multipliers with a reflective photocathode deposited on the surface of the first multiplying element are very attractive devices for photon detection and imaging over large area at moderate cost. They combine production and operation simplicity, high sensitivity to single photons, fast time response and accurate localization. In this work we present in detail the mechanisms governing the operation of these photon detectors. The results of electron extraction, transfer, multiplication and detection processes in this multi-element structure are presented and analyzed. We discuss the role of important elements and parameters influencing the detector’s operation and performance: the GEM geometry, the choice of the different electric fields and the gas mixture.

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1. Introduction

Gas Avalanche Photomultipliers (GPMTs) based on cascaded Gas Electron Multipliers [1] (GEM) coupled to semi-transparent photocathodes have been extensively studied for UV-photon imaging. Due to minimal photon-feedback and limited ion-feedback effects in these multiplying structures [2–5], they operate reliably, with single-photon sensitivity, at gains exceeding $10^6$, in atmospheric pressure gases, including noble gas mixtures [2] and CF$_4$ [6]. These detectors can operate at magnetic fields and have good time [6,7] and position [8] resolutions. Multi-GEM GPMTs combining standard GEMs and semi-transparent bi-alkali photocathodes are currently being developed for the visible spectral range [9,10]. Recently, we reported on the successful operation of GEM-based GPMTs having a reflective CsI UV-photocathode deposited directly on the top face of the first GEM [11,12] (see Fig. 1). Compared to semi-transparent photocathodes, the reflective ones have a higher quantum efficiency (QE) and are simpler to produce as no thickness optimization is required. Furthermore, in this detector geometry,

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the photocathode is completely concealed from avalanche-generated photons. High gains exceeding 10^6 for single photoelectrons were reached with this detector in a variety of gases, including noble gas mixtures [7]. This permits the conception of large-area photon imaging detectors, sensitive to single photons. We recently reported on the results of our extensive study of ion back-flow reduction in cascaded multi-GEM detectors [13], important for reducing ion-feedback effects. The latter have a considerable impact on the stability of operation of gaseous detectors, particularly of visible-sensitive GPMTs [10]. A further reduction of ion backflow could be obtained in cascaded GEMs followed by the novel Micro-Hole & Strip Plate (MHSP) multiplying element [14]. Cascaded reflective-GEM GPMTs have numerous potential applications for imaging UV-to-visible photons. UV detectors of this type are currently being developed for the hadron-blind Cherenkov Detector of PHENIX (RHIC-BNL) [15].

In this article we summarize our principal results regarding the reflective photocathode GPMT; we discuss in detail the mechanisms governing its operation, particularly photoelectron extraction and transfer from the photocathode to the multiplying stages and the influence of the GEM geometry and the choice of the gas mixture on the electron transfer processes. A detailed discussion on the optimal choice of operation parameters is provided.

2. Single photoelectron detection efficiency

The photon detection efficiency in GPMTs is the product of two parameters: the QE of the photocathode and the single-photoelectron detection efficiency, \( e_{\text{det}} \), of the detector. The quantum efficiency, the probability of electron emission per incoming photon, is an intrinsic property of the photocathode; it depends on the photocathode material, the status of its surface, and the photon wavelength. When operated in a gas environment, the QE is reduced by photoelectron backscattering [16]; the effective QE is the product of the QE and the efficiency of extracting electrons from the photocathode into the gas. A review on UV-sensitive CsI photocathodes and their operation under gas multiplication can be found in Ref. [17].

The single-electron detection efficiency of the detector depends on many parameters: the detector geometry, the gas mixture, the electric field conditions, the multiplier gain, etc. Once emitted from the photocathode surface into gas, the photoelectron has to be extracted from its vicinity and transferred into the first amplifying stage of the detector. The mechanism of electron extraction, transfer and multiplication in cascaded GEMs with semi-transparent photocathodes were systematically studied in [18,19].

The possible fate of the photoelectron in the case of a GEM-based GPMT with reflective photocathode, is schematically shown in Fig. 2 as steps (a)–(c):

(a) Photoelectrons are extracted from the photocathode with an efficiency \( e_{\text{extr}} \). Elastic collisions of the photoelectrons with gas molecules cause a fraction of the photoelectrons to backscatter to the photocathode and be reabsorbed. This well-studied effect [16] reduces the effective quantum efficiency of the photocathodes operated in gas compared to their operation in vacuum. A proper choice of
the gas mixture, having a low cross-section for elastic electron scattering (e.g. pure noble gases have large elastic cross sections), and high electric fields at the photocathode surface (typically \( \geq 1 \) kV/cm at atmospheric pressure), minimize the photoelectron backscattering and values of \( \varepsilon_{\text{extr}} \) approaching unity can be reached [6].

(b) Following extraction, the photoelectrons drift in the electric field into the GEM apertures with a probability \( \varepsilon_{\text{hole}} \). Due to diffusion in gas, not all photoelectrons enter the apertures—some may be collected at the top GEM electrode. In conditions with reversed drift field, electrons may also be lost on the cathode mesh, above the photocathode. Both processes result in a reduced \( \varepsilon_{\text{hole}} \). Photoelectrons that enter the aperture encounter high electric fields, of \( \sim 30–100 \) kV/cm, and undergo gas amplification; the exact multiplication experienced by an individual photoelectron is statistically distributed according to Polya’s formula [20], which in the case of “unsaturated” multiplication reduces to a simple exponential distribution. In other words, a large fraction of the single-photoelectrons experience only a small multiplication and thus only a small number of electrons arrives at the GEM-hole exit.

(c) As electron losses due to their partial collection on the bottom-GEM (see Fig. 2) electrode are unavoidable [21], there are events in which all avalanche-electrons are lost and none reach the next GEM stage. Thus \( \varepsilon_{\text{trans}} \), the probability that at least a fraction of the event charge is transferred to the next multiplier stage and the event is recorded on the anode, may not be large. In fact, this loss mechanism is particularly critical in the case of single-photoelectron detection due to avalanche statistics discussed above. On the contrary, for a large number of primary photoelectrons, the electron avalanche is large and the probability of total electron loss to the bottom-GEM electrode is negligible, even at moderate multiplication, resulting in \( \varepsilon_{\text{trans}} \) values of close to unity.

The single-photoelectron detection efficiency can thus be described as

\[
\varepsilon_{\text{det}} = \varepsilon_{\text{extr}} \cdot \varepsilon_{\text{hole}} \cdot \varepsilon_{\text{trans}}.
\]

For convenience we also define a photoelectron collection efficiency, \( \varepsilon_{\text{coll}} \); it is the efficiency whereby photoelectrons are extracted from the photocathode and guided into the GEM apertures

\[
\varepsilon_{\text{coll}} = \varepsilon_{\text{extr}} \cdot \varepsilon_{\text{hole}}.
\]

3. Experimental setup and methodology

Our principal aim was to measure the absolute single-electron detection efficiency. It was done by recording UV-induced single-electron pulses from a photocathode deposited on a GEM (Fig. 3) and using their yield for deriving the various electron
transport efficiencies defined in Section 2. This method is very different from the approach based on DC current measurements [22,15]. As explained above, resulting from the statistical fluctuations in the amplification process of single electrons, many events have only a small number of electrons at the GEM hole exit. DC current measurements are not sensitive to the loss of single photoelectrons or to events with small gain, as their contribution to the total current is negligible when the detector is operated in multiplication mode. Under these conditions, the only way to assess the single-electron detection efficiency $e_{\text{det}}$, is by single electron pulse counting.

We found it convenient to measure $e_{\text{det}}$ by comparing the pulse-counting rate from the GEM–GPMT with reflective CsI to the one measured with a multiwire-based GPMT having the same photocathode illuminated by the same light source. Fig. 3 shows the experimental setup consisting of a GEM foil, whose top side is evaporated with CsI, sandwiched between two MWPC detectors. By a proper choice of potentials, two operation modes are possible:

- In the GEM mode, photoelectrons released from the photocathode are guided into the GEM holes and further transferred to the MWPC$_{G}$ structure, where they are further multiplied and recorded.

- Measurements in the MWPC mode are used for normalizing the GEM-mode results. The CsI coated face of the GEM acts simply as a reflective photocathode with the uncoated face kept at the same potential. Emitted photoelectrons are multiplied and detected by the MWPC$_{M}$ structure.

The advantage of this approach is the possibility for a direct evaluation of the efficiency of extracting electrons from the photocathode and transferring them into the GEM apertures and further towards the following multiplying element. In both modes, the MWPC provides the main electron amplification for the detection.

The sensitive area of the detector used here (Fig. 3) is $30 \times 30$ mm$^2$. All meshes are made of 50 μm diameter crossed stainless-steel wires, 500 μm apart (81% optical transparency). The MWPC anode wires are 10 μm in diameter and 1 mm apart. The distances between the various electrodes are all 1.6 mm, except between the uncoated GEM side and M3 where a 2.6 mm gap was used. We investigated GEMs of different geometries and the resulting influence on the single electron detection efficiency. The geometrical parameters of the GEMs are listed in Table 1. All GEMs are CERN-made$^1$ and have the copper cladding plated with a thin Ni/Au layer to provide a stable and inert substrate for photocathode deposition.

The top side of the GEM was covered with a 2500 Å thick layer of CsI, vacuum deposited at a rate of 10–20 Å/s. The absolute quantum efficiency (QE) of a CsI photocathode deposited on a dci40 GEM (Table 1) was measured with a calibrated UV-monochromator system. It was found to be 36% at 150 nm [12], in agreement with previously published data of good quality CsI photocathodes [17], considering the 23% loss of active area due to the holes. The exposure time of

\[ E_{\text{trans}} \]

\[ E_{\text{drift}} \]

\[ \Delta V_{\text{GEM}} \]

Fig. 3. The experimental setup used for measuring the single-photoelectron detection efficiency, consisting of a CsI coated GEM, sandwiched between two MWPC amplification elements.

$^1$CERN printed circuit workshop.
the photocathode to air during assembly was limited to $\approx 10$ min, which should hardly affect its QE [17].

The detector was placed in a vacuum vessel and evacuated to $10^{-5}$ Torr prior to its operation. The gas flow and pressure were regulated with mass flow controllers and differential pumping.

Measurements were carried out in current-mode and pulse counting-mode, to assess the photoelectron detection efficiency and to pinpoint the photoelectron transfer through the GEM. The various electrical connection schemes are shown in Fig. 4.

In conditions without gas amplification, currents measured on the detector electrodes are due to transfer of photoelectrons only, and thus provide a useful tool for unambiguous evaluation of the charge transfer process. In the MWPC current mode the photocurrent is measured on the
mesh M2, with a negative potential applied to the interconnected GEM electrodes (see Fig. 4a). The drift field, \( E_{\text{drift}} \), extracts the photoelectrons and guides them to the mesh M2. As can be seen in Fig. 5, the current \( I_{\text{MWPC}} \) rises fast with \( E_{\text{drift}} \) and then saturates at a plateau with a very shallow slope. This behavior reflects the drop of photoelectron backscattering at high fields. Increasing the drift fields further reduces electron backscattering resulting in slowly increasing \( I_{\text{MWPC}} \). For normalization of the current measurement in the GEM-mode, the value of \( I_{\text{MWPC}} \) at 3 kV/cm was chosen. This seemingly arbitrary choice can be justified by the fact that photocurrents above that value rise very moderately in all gases under investigation. Higher drift field values are not recommended as they will lead to photoelectron losses when these are transmitted to the MWPC through the mesh M2 (from high to low field).

In the GEM current mode the current \( I_{\text{GEM}} \) was measured on the interconnected GEM bottom and M3 electrodes while a negative potential was applied to the top-GEM electrode (Fig. 4b). The thus-defined GEM voltage, \( \Delta V_{\text{GEM}} \), extracts the electrons from the photocathode and guides them into the GEM holes. The transferred current \( I_{\text{GEM}} \), normalized to \( I_{\text{MWPC}} \) measured in the MWPC current mode provides an unambiguous measure of the collection efficiency, \( e_{\text{coll}} \).

As explained above, in gas multiplication conditions, single-photoelectron pulse counting is the only reliable way of measuring the single-electron detection efficiency. Here, the counting rates in GEM and MWPC modes were measured under illumination with a constant source rate. In the MWPC mode, the photoelectrons are extracted by the drift field \( E_{\text{drift}} \), transferred through the mesh M2 and multiplied on the wires of MWPC-M. In the GEM mode, photoelectrons are guided into the GEM holes where they experience a first multiplication. The multiplied charge is then transferred in the transfer field \( E_{\text{trans}} \) to the second amplification stage MWPC-G.

The charge signals from the MWPCs, in the MWPC and GEM modes, were recorded with a multi-channel-analyzer. The spectra were unsaturated Polya distributions having exponential shape as shown in Fig. 6. The ratio of the counting rates recorded in the GEM- and MWPC-modes defines a “practical” single-electron detection efficiency \( e_{\text{det}} \).

![Fig. 5. Photocurrent measured on the mesh M2 in the MWPC current-mode in Ar/CH<sub>4</sub> (50:50).](image)

![Fig. 6. Single-electron pulse-height spectra measured in (a) GEM-mode (Fig. 4d, \( V_{\text{GEM}} = 510 \text{ V} \), \( E_{\text{drift}} = 0 \), \( E_{\text{trans}} = 5 \text{ kV/cm} \)) and (b) MWPC-mode (Fig. 4c, \( E_{\text{drift}} = 3 \text{ kV/cm} \)) in CH<sub>4</sub> at atmospheric pressure.](image)
GEM gain measurements were performed in a different setup by combining a GEM with a semi-transparent CsI photocathode illuminated by a constant flux UV lamp. The initial photocurrent (without multiplication) extracted from the photocathode was measured for a drift field of 3 kV/cm on the interconnected faces of the GEM. Under multiplication, the GEM was operated with a drift field of 3 kV/cm between the photocathode and the top GEM face with varying GEM voltages \( \Delta V_{\text{GEM}} \). The current resulting from charge multiplication was collected on the bottom side of the GEM. Normalizing it to the initial photocurrent gives a direct measure of the GEM gain. In all conditions the total current was limited to 10 nA by the use of optical absorbers in the light path.

For calculating the electric fields and simulating the electron drift lines we used the finite-element programs Maxwell 3D [23] and Garfield [24], respectively.

4. Role of the electric fields

The electric fields configuration in the detector is the main factor influencing the single photoelectron detection efficiency, as it is responsible for the efficient photoelectron extraction from the photocathode, its focusing into the GEM holes and the efficient extraction of a fraction of the avalanche charge from the first GEM to the following multiplier stage. This section describes how the various detector potentials influence these relevant efficiencies.

The figures in this section were not chosen systematically but rather according to how well they illustrated the discussed effects. Therefore, the GEM geometry and the gas mixture vary among the figures presented. A systematic discussion of the influence of the GEM geometry and the gas mixture follows in Sections 5 and 6, respectively.

4.1. Role of the GEM potential \( \Delta V_{\text{GEM}} \)

The potential difference across the GEM, \( \Delta V_{\text{GEM}} \), has two effects on the single-electron detection efficiency. Firstly, it creates an electric field on the top-GEM surface, permitting efficient extraction of photoelectrons from the photocathode and guiding them into the GEM holes. Fig. 7 illustrates this point, showing simulated electron drift paths on a sc50 GEM (Table 1) for \( \Delta V_{\text{GEM}} = 500 \) V. One should notice that due to field penetration into the drift region it is not field free, though equal potentials are applied to the top GEM electrode and the cathode mesh above. Secondly, photoelectrons entering the GEM apertures experience gas multiplication in the strong electric fields within the holes, resulting in a Polyak-distributed number of electrons at the hole exit. The influence of the GEM gain on the single-photoelectron detection efficiency can only be measured in pulse counting mode and is discussed in Section 4.3.

The electric field created at the top-GEM surface by the GEM potential is highly non-homogeneous. It is strongest at the hole circumference and drops strongly towards the center between the holes; its value at the center is \( \sim 1.5 \) kV/cm. Fig. 8 shows the electric field strength variation on the photocathode surface along a line between neighboring holes for three different values of \( \Delta V_{\text{GEM}} \). At \( \Delta V_{\text{GEM}} = 500 \) V,
the field strength ($E > 2.5$ kV/cm) is sufficiently high all over the surface to minimize backscattering in most gases.

The photocurrent versus GEM voltage, depicting the collection efficiency, $e_{\text{coll}}$, of a dci140 GEM in atmospheric CH$_4$ is shown in Fig. 9. One can remark that already for a value of $\Delta V_{\text{GEM}} = 100$ V more than 80% of the photoelectrons are extracted from the photocathode and transferred into the GEM holes. For $\Delta V_{\text{GEM}}$ values above $\sim 130$ V, multiplication in the GEM holes makes the measurement in current mode irrelevant for extracting $e_{\text{coll}}$.

4.2. Role of the drift field $E_{\text{drift}}$

The drift field $E_{\text{drift}}$, defined by the potential difference between the top GEM and the electrode mesh M2 (see Fig. 3), modifies the electric field created by the GEM potential in the vicinity of the photocathode. Its influence on the collection efficiency can be seen in Fig. 10, showing the variation of the current measured in the GEM-mode, $I_{\text{GEM}}$, as a function of $E_{\text{drift}}$ for a dci140 GEM operated in atmospheric Ar/CH$_4$ (20:80) at $\Delta V_{\text{GEM}} = 200$ V. In addition to $I_{\text{GEM}}$, we also measured the current on the photocathode, $I_{\text{pc}}$; it has opposite polarity than $I_{\text{GEM}}$, as it corresponds to the flow of photoelectrons leaving the photocathode, but for an easier comparison, only the...
absolute values of the currents are plotted. The maximal value of $I_{GEM}$ is reached when operating the detector with $E_{\text{drift}} = 0$. For both negative and positive $E_{\text{drift}}$ values, the current on the GEM $I_{GEM}$ drops considerably, and therefore also the collection efficiency $e_{\text{coll}}$. In the case of positive drift field values, the electric field strength on the photocathode is reduced, resulting in higher backscattering and a lower extraction efficiency, $e_{\text{extr}}$. The simultaneous drop of the photocathode current $I_{pc}$ confirms this interpretation. In the case of negative drift field values, leading to an increased electric field strength on the photocathode surface, the photocurrent $I_{pc}$ increases slightly due to reduced backscattering and thus increased extraction efficiency $e_{\text{extr}}$. But a large fraction of the extracted photoelectrons are collected on mesh M2 above the photocathode rather than being transferred into the GEM holes, resulting in a smaller $e_{\text{hole}}$ and the observed drop in $I_{GEM}$.

In a pulse-counting mode, the counting rate measured in the GEM-mode shows the same behavior: it has its maximum for $E_{\text{drift}} = 0$, as can be seen in Fig. 11 for a dc140 GEM operated in Ar/CH$_4$ (50:50) at $\Delta V_{GEM} = 350$ V. The width of the distribution in this case is much larger than in the previous figure, the reason being the higher value of $\Delta V_{GEM}$ used, diminishing the effect of the drift field. For still higher $\Delta V_{GEM}$ values, the influence of $E_{\text{drift}}$ is expected to be even smaller.

In the optimal operation of the detector with $E_{\text{drift}} = 0$, the electric field configuration on the photocathode is determined only by the GEM potential. In all further measurements the potentials were chosen accordingly.

A multi-GEM GPMT with a reflective photocathode is ideally suited for photon detection in environments with a high background of ionizing radiation. When operated with a small negative drift field and high $\Delta V_{GEM}$, the loss in photoelectron collection efficiency, $e_{\text{coll}}$ is negligible and the detector is practically insensitive to the ionizing radiation, as only electrons created close to the photocathode surface are transferred into the GEM holes. The negative drift field ensures that the majority of the particle-induced ionization electrons in the drift gap are collected on the mesh, thus considerably reducing background events. A triple-GEM detector with a reflective CsI photocathode operated with a small negative drift field is currently under study for a hadron-blind Cherenkov detector of the PHENIX experiment at RHIC (BNL) [15].

### 4.3. Role of the transfer field and GEM gain

Electrons leaving the first multiplying stage are extracted and transferred to the following multiplying stage by the transfer field $E_{\text{trans}}$, in our case defined as the potential difference between the bottom-GEM electrode and mesh M3 of the MWPC$_G$ (see Fig. 3). As discussed above, in GEM multipliers a fraction of the avalanche electrons is lost, being collected on the bottom-GEM electrode [21,22]. The fraction of the extracted charge grows approximately linear with the increasing transfer field $E_{\text{trans}}$. To demonstrate this effect, the current measurement setup described in Section 3 was slightly modified by individually powering the bottom-GEM and M3 electrodes, thus allowing for varying $E_{\text{trans}}$. The currents on all electrodes were recorded: the transfer current $I_{\text{trans}}$ on mesh M3, the current on the bottom-GEM electrode $I_{GEM}$ and the current on the photocathode $I_{PC}$, interconnected.
with mesh M2. \( I_{PC} \) has an opposite polarity to the other two currents, corresponding to electrons leaving the photocathode and, in the case of amplification, also to the collection of ions generated in the avalanche process. The sum of all three currents is zero. For the clarity of presentation, only the absolute values of the currents versus \( E_{trans} \) are plotted in Fig. 12. The measurement was performed in atmospheric CH\(_4\) with a sc50 GEM at \( \Delta V_{GEM} = 400 \) V. The higher the transfer field, the larger the charge which is extracted from the GEM towards M3, explaining the increasing \( I_{trans} \) and the dropping \( I_{GEM} \). The slight increase of \( I_{PC} \) with \( E_{trans} \) can be explained by a small gain increase in the GEM caused by the higher transfer field [25].

For higher \( \Delta V_{GEM} \) values, higher transfer fields are required to overcome the GEM field and to extract the same charge fraction form the GEM holes. This can be seen in Fig. 13a, showing the transferred current \( I_{trans} \), the current on the bottom-GEM electrode \( I_{GEM} \) and the photocathode current \( I_{PC} \), as function of \( \Delta V_{GEM} \), measured at atmospheric CH\(_4\) on a sc50 GEM with a constant transfer field \( E_{trans} = 3 \) kV/cm. Up to \( \Delta V_{GEM} \sim 150 \) V the measured currents are due only to transfer of photoelectrons; for higher GEM voltages amplification in the GEM holes starts, resulting in a fast rise of the currents with increasing \( \Delta V_{GEM} \). In Fig. 13b, showing \( I_{trans} \) and \( I_{GEM} \) normalized to \( I_{PC} \), the influence of \( \Delta V_{GEM} \) on the charge transfer can be seen more clearly: for \( \Delta V_{GEM} \sim 100 \) V, the transfer field is strong enough to extract almost all electrons from the GEM holes. For higher GEM potentials, \( I_{trans} \) drops and \( I_{GEM} \) increases, as the relative strength of the transfer field decreases compared to the GEM field. Therefore, high values of \( E_{trans} \) have to be chosen, in order to extract a large fraction of the avalanche charge from the GEM and transfer it to the next amplification stage. It is reported [22], that in multi-GEM detectors, high transfer fields

![Fig. 12. Influence of \( E_{trans} \) on the charge extraction from the GEM holes for constant \( \Delta V_{GEM} = 400 \) V, measured on a sc50 GEM in atmospheric CH\(_4\).](image1)

![Fig. 13. (a) The variation of the detector currents as a function of \( \Delta V_{GEM} \), measured with a sc50 GEM in atmospheric CH\(_4\) for a constant \( E_{trans} \), and (b) normalized to the photocathode current \( I_{PC} \).](image2)
result in electron losses at the top electrode of the following GEM stage. In our measurements, where the second stage is a MWPC, this effect was not observed in the pulse-counting mode (Fig. 14). We attribute this to the higher electron transparency of the mesh M3 compared to that of a GEM. Nevertheless, for our multi-GEM GMDET application, transfer field values of 3–4 kV/cm were chosen in further experiments, providing a good charge transfer into a second stage GEM in multi-GEM detectors [22].

The single-photoelectron detection efficiency $\varepsilon_{\text{det}}$ is shown in Fig. 15 as a function of $\Delta V_{\text{GEM}}$ for three different transfer field values; it provides more proof of the importance of operating with high transfer fields. As expected, the highest transfer field applied $E_{\text{trans}} = 3.8$ kV/cm yields the best result, of a full single-electron detection already at $\Delta V_{\text{GEM}} = 400$ V. Full photoelectron detection efficiency is also reached for a smaller transfer field of $E_{\text{trans}} = 1.9$ kV/cm although at higher $\Delta V_{\text{GEM}}$ values and therefore higher gain. In the case of a very small transfer field of $E_{\text{trans}} = 0.4$ kV/cm, the counting rate even drops with increasing values of $\Delta V_{\text{GEM}}$ due to the above described effect of higher charge losses to the bottom-GEM electrode for high $\Delta V_{\text{GEM}}$ values.

In all three cases the counting rate increases once the GEM field is sufficiently high for reaching gas multiplication, at $\Delta V_{\text{GEM}} \sim 300$ V. Although the transferred charge fraction for each event decreases for higher values of $\Delta V_{\text{GEM}}$, the GEM gain compensates for these losses, i.e. only a fraction of the avalanche charge has to be transferred to the successive multiplication stage to reach a unity transfer efficiency. For higher GEM fields and therefore higher gains, the average avalanche size increases and the chance of losing all electrons belonging to this event to the bottom-GEM electrode is considerably smaller. The upper scale in Fig. 15 shows the gain corresponding to the GEM voltage shown on the bottom scale. As the charge fraction lost to the bottom-GEM electrode is higher for lower transfer fields, the gain required for compensating for these losses is also higher. Therefore it is advisable to operate the detector with high transfer field values for reaching high single-photoelectron detection efficiencies, even at modest gains of the GEM carrying the photocathode.
5. Role of the GEM geometry

GEMs with different geometries were investigated (see Table 1), for assessing the role of changes in the following parameters (with respect to that of the standard GEM geometry dc140): the pitch (dc200), the hole diameter (dc100), the hole shape (sc50, sc25) or the GEM thickness (sc25), in possible improving single-photoelectron detection efficiency, $\varepsilon_{\text{det}}$.

The most obvious impact of the GEM geometry is the effective surface area for photocathode deposition. This varies in our case from 89% to 53% for the dc200 and dc100 geometries, respectively; the standard GEM (dc140) has an active surface of 77%. Maximizing the available photocathode surface favors GEMs with a small hole-to-total-area aspect ratio. On the other hand, as was discussed in Section 4.1, a high electric field strength on the photocathode surface is required to overcome photoelectron backscattering and to guide the electrons into the GEM holes, which favors a high hole-to-total-area aspect ratio. This is demonstrated by the simulation results in Fig. 16; it shows the variation of the electric field strength over the photocathode area for constant $\Delta V_{\text{GEM}}$.

The effect is demonstrated in the current-mode measurement of the collection efficiency $\varepsilon_{\text{coll}}$, presented in Fig. 17. With the dc100 GEM, almost full collection efficiency was reached at $\Delta V_{\text{GEM}} \approx 100$ V, while for the dc200 geometry only $\approx 50\%$ of the photoelectrons are collected at the same GEM voltage; this is due to the difference in electric field strength on the photocathode surface. Again, the dc140 standard GEM geometry results fall in-between that of the dc100 and dc200 GEMs, reaching 80% efficiency at $\Delta V_{\text{GEM}} = 100$ V. In addition, the results for the two remaining geometries sc50 and sc25 are also shown. The difference in collection efficiency of these two from that of the dc140 GEM, despite the same hole-to-total-area ratio, is attributed to the different hole shape and in the case of sc25, also to the thickness of the GEM. A higher collection efficiency is observed for the sc25 GEM, compared to that of the dc140 and sc50; it can be explained by the thinner (25 $\mu$m) Kapton foil of the sc25 GEM, resulting in higher field strengths at the photocathode surface for the same $\Delta V_{\text{GEM}}$ and $\varepsilon_{\text{coll}}$.
thus a reduced photoelectron backscattering. A slightly lower field on the photocathode surface for GEMs with conical holes for small GEM voltages, is probably responsible for the slightly lower collection efficiency of the sc50 GEM.

For all GEM geometries, with the exception of dc200, collection efficiencies exceeding 80% at $\Delta V_{\text{GEM}} = 100$ V were reached, where gas amplification starts and current measurements are no longer reliable.

As was discussed in Section 4.3, the transfer efficiency $\varepsilon_{\text{trans}}$ has a strong influence on the single photoelectron detection efficiency. The charge loss to the bottom-GEM electrode can be modified by the hole shape. GEMs with conical holes operated with the large hole opening facing the transfer region, show considerably lower electron losses to the bottom-GEM electrode, when compared to the standard double-conical ones. This effect is demonstrated in Fig. 18, showing the single-photoelectron detection efficiency, $\varepsilon_{\text{det}}$, as a function of $\Delta V_{\text{GEM}}$, measured in pulse-counting mode in atmospheric CH$_4$. Both GEMs with conical holes, sc25 and sc50 show higher single-photoelectron detection efficiency than the standard GEM. This can only be due to a higher transfer efficiency $\varepsilon_{\text{trans}}$, as the collection efficiency of these GEMs is comparable to that of the standard GEM geometry (see Fig. 17). Even the dc100 geometry with its double-conical holes, showing the highest collection efficiency, has a lower overall detection efficiency, due to a small transfer efficiency.

Surprisingly, all five GEM geometries investigated showed practically the same gain-voltage characteristics (Fig. 19). The sc25 GEM proved to be very fragile in operation, probably due to the thin (25 $\mu$m) insulator; a single discharge would cause permanent damage to the GEM, preventing further operation, while the other GEMs could withstand several discharges without noticeable degradation. This rather discards the use of the sc25 GEM geometry in a detector assembly, despite its higher $\varepsilon_{\text{det}}$ at low fields (Fig. 18).

Maximal detection efficiency was reached at $\Delta V_{\text{GEM}} \sim 600$ V with the dc100 and the sc50 GEM geometries, corresponding to a gain of $\sim 100$. Even with the standard GEM geometry sc140, a single-photoelectron detection efficiency of $\sim 90\%$ was reached at $\Delta V_{\text{GEM}} = 550$ V.

Besides the obvious influence of the geometry on the effective photocathode’s surface area, the strongest influence on the single-electron detection efficiency is due to the hole shape. The improved transfer efficiency of GEMs with conical holes, could advocate for their use as a first-stage in multi-GEM GPMs with reflective photocathodes. However, reports pointing to an enhanced up-charging of these GEMs, due to the large surface of insulator in the holes exposed to...
back-drifting avalanche ions, have to be considered [21,22].

6. Role of the gas composition

The choice of the gas mixture influences the detector operation in various ways. Firstly, operation voltages vary considerably for different gases, as reflected in the gain curves in Fig. 20. For example, CH$_4$ and CF$_4$ require much higher operation voltages compared to Ar/CH$_4$ (95:5). CH$_4$ is often used in MWPC-based GPMTs, providing stable operation [26]; it has very low photoelectron backscattering, which yields high effective QE values. Ar/CH$_4$ (95:5) is our current gas mixture of choice for operation of sealed GPMTs with visible-sensitive photocathodes [9,10], the main reasons being low operating voltages, stable operation with reduced secondary effects, relatively low electron-backscattering and a small fraction of organic quencher. The second Ar/CH$_4$ mixture of (20:80) was investigated in an attempt to further reduce backscattering and keep the operation voltages relatively low. CF$_4$ has been studied for windowless Cherenkov detectors, including RICH, where the radiator gas is also the counting gas [6,15]. Operation of our present setup in pure CF$_4$, with the MWPC and CsI photocathode was not possible due to photon-mediated secondary effects, caused by gas scintillation light and avalanche-photon feedback; these limited the gain, which prevented us from performing the usual normalization measurements discussed above. Instead, the pulse-counting rate in the MWPC mode was measured in pure CH$_4$ and used for normalization of the CF$_4$ results measured in the GEM-mode. Here, due to the suppression of photon feedback by the GEM, no secondary effects were observed, resulting in stable high gain operation in CF$_4$ (Fig. 20). The absence of photon feedback, permitted reaching high gain operation in pure CF$_4$ also in cascaded multi-GEM detectors coupled to semi-transparent photocathodes [6]. For the same reason such detectors could also operate at high gains in noble gas mixtures, at considerably lower operation voltages [2]. Gains exceeding $10^6$ were reached in atmospheric CF$_4$, in cascaded GEMs with reflective CsI photocathodes [7].

The different operation voltages for the different gas mixtures have several consequences: on one hand, higher GEM potentials increase the electric field on the photocathode surface and therefore reduce photoelectron backscattering. On the other hand, as was discussed in Section 4.3, for fixed transfer fields $E_{\text{trans}}$, electron losses at the hole exit are larger for high $\Delta V_{\text{GEM}}$ values, which tends to decrease $\delta_{\text{trans}}$.

As already discussed above, electron backscattering to the photocathode which has direct consequence on the effective QE, varies considerably with the gas mixture [2,6,16]. While CF$_4$ and CH$_4$ have the highest known extraction efficiency even at moderate field strengths ($\sim 90\%$ at 1 kV/cm [6]), in Ar/CH$_4$ (95:5) an extraction of only 70% can be reached at equal field strengths. Electron extraction in noble gases and their mixtures is more difficult at moderate fields [16,27]. This difference in backscattering manifests itself in the different collection efficiencies presented in Fig. 21 for a sc50 GEM geometry. The three gases with low backscattering CF$_4$, CH$_4$ and Ar/CH$_4$ (20:80) show collection efficiencies of $\sim 70\%$ at $\Delta V_{\text{GEM}} = 50$ V, while for Ar/CH$_4$ (95:5) the high backscattering lowers the extraction.
efficiency to the 25% levels at equal GEM fields. The early onset of amplification in the GEM holes for this gas makes the measurement of $\varepsilon_{\text{coll}}$ unreliable at values of $\Delta V_{\text{GEM}}$ higher than $\sim 50$ V.

Nevertheless full single-electron detection efficiency was reached in all four gases as can be seen in Fig. 22. With the exception of CF$_4$, in which a dc140 GEM was used, the measurements were performed with a sc50 GEM. Due to the low operation voltages required, full single photoelectron detection efficiency is reached in Ar/CH$_4$ (95:5) already at $\Delta V_{\text{GEM}} \sim 350$ V; in the other gas mixtures: Ar/CH$_4$ (50:50), pure CH$_4$ and CF$_4$, the detection efficiency reaches unity values at, respectively, increasing GEM voltages (Fig. 22a).

If plotted as a function of single-GEM gain (Fig. 22b) CH$_4$ and Ar/CH$_4$ require only a gain of 30 and 80, respectively, in order to reach full detection efficiency. For Ar/CH$_4$ (95:5) the low operation voltage and the high backscattering require higher gains ($\sim 300$). The use of a dc140 GEM in CF$_4$ requires gains exceeding $10^3$ to overcome losses to the bottom-GEM electrode and reaching full efficiency. It is expected that the CF$_4$ operation with a sc50 GEM should yield similar results to that in pure CH$_4$.

7. Summary and conclusion

We discussed the operation of gaseous photomultipliers incorporating a GEM coated with a reflective CsI photocathode. The use of reflective photocathodes results in higher quantum efficiency, better stability and easier production. We demonstrated that full single-photoelectron detection efficiency can be reached when the operation
conditions are correctly chosen. The field above the GEM, $E_{\text{drift}}$, should be very small, approaching zero, to allow a good focusing of the photoelectrons into the GEM holes by the GEM electric field. A small reversed drift field makes the detector practically insensitive to ionizing particles; this is a rather unique property of this detector, permitting its stable operation at high radiation background. The transfer field, $E_{\text{trans}}$ below the GEM, should be chosen as high as possible, to guarantee a high electron extraction from the GEM holes, but without suppressing the electron collection into the subsequent multiplication element. The GEM potential, $\Delta V_{\text{GEM}}$, is crucial, as it creates the electric field that extracts the photoelectrons from the photocathode surface and guides them into the GEM holes. Furthermore, the amplification in the GEM holes is important for minimizing events loss due to electron losses to the bottom-GEM electrode at the hole exit.

Different GEM geometries were tested, demonstrating the advantage of GEMs having conical hole shapes. Operated with the wide opening towards the next multiplier stage, the higher charge extraction results in higher transfer efficiencies and thus allows full single-photoelectron detection at relatively low GEM gains. Nevertheless, GEMs with double-conical hole shapes also yielded full single-photoelectron detection in CF$_4$, albeit at higher gains.

In all gases investigated, Ar/CH$_4$ (95:5) and (20:80), pure CH$_4$ and CF$_4$, full single-photoelectron detection efficiency was reached. Gases with low electron backscattering require lower fields at the photocathode surface, for efficient operation and therefore smaller $\Delta V_{\text{GEM}}$ values are needed.

GEMs coated with CsI are successfully operated at high gains, exceeding $10^6$ [7], which facilitates the detection and imaging of single photoelectrons. The production of reflective photocathodes on top of the GEM surface is simple. Such cascaded GEM detectors have no photon feedback; they have considerably reduced ion-feedback, which can be eliminated by gating the detector [13,3]. In comparison with cascaded GEMs with semitransparent photocathodes [2,18], this configuration has very low sensitivity to ionizing background radiation. All these properties make cascaded-GEM GPMTs with reflective photocathodes a suitable choice for photon detection, down to the single-photon levels, over large area at moderate cost. Such detectors are indeed being for a hadron-blind Cherenkov detector of the relativistic heavy ion PHENIX experiment (RHIC-BNL) [15].

Further investigations of cascaded-GEM detectors are underway in our group, including ion backflow suppression, imaging GPMTs, sealed operation of visible-sensitive GPMTs, etc.

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