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Cryogenic Gaseous Photomultiplier for Position Reconstruction of Liquid Argon Scintillation Light

B. Lopez Paredes^{a*}, C.D.R. Azevedo^b, S. Paganis^{c†}, A.L.M. Silva^b, N.J.C. Spooner^a and J.F.C.A. Veloso^b

^a*Department of Physics and Astronomy, University of Sheffield,
Hicks Building, Hounsfield Rd, S3 7RH, United Kingdom*

^b*I3N, Department of Physics, University of Aveiro,
3810-193, Aveiro, Portugal*

^c*Department of Physics, National Taiwan University,
No 1, Sec 4, Roosevelt Road, Taipei 10617, Taiwan
E-mail: brais.lopez.paredes@cern.ch*

ABSTRACT: Presented here are first tests of a Gaseous Photomultiplier based on a cascade of Thick GEM structures intended for gamma-ray position reconstruction in liquid argon. The detector has a MgF₂ window, transparent to VUV light, and a CsI photocathode deposited on the first THGEM. A gain of $8 \cdot 10^5$ per photoelectron and $\sim 100\%$ photoelectron collection efficiency are measured at stable operation settings. The excellent position resolution capabilities of the detector (better than 100 μm) at 100 kHz readout rate, is demonstrated at room temperature. Structural integrity tests of the detector and seals are successfully performed at cryogenic temperatures by immersing the detector in liquid Nitrogen, laying a good foundation for future operation tests in noble liquids.

KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc), Noble liquid detectors (scintillation, ionization, double-phase), Photon detectors for UV, visible and IR photons (gas) (gas-photocathodes, solid-photocathodes), Gaseous imaging and tracking detectors.

*Corresponding author.

†Most of the work performed while at University of Sheffield

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1. Introduction

Noble liquids (xenon, krypton and argon) are growing in importance in particle physics experiments [1–5] and they have been proposed as an alternative to crystals in medical particle detectors such as Positron Emission Tomography (PET) scanners [6]. In PET scanners, the position resolution is limited by the granularity of the 360° crystal and photomultiplier tube (PMT) arrays, and the energy resolution by the crystal scintillation light yield (NaI(Tl): 38 ph/keV, BGO: 15% relative to NaI(Tl), GSO: 30%, LSO: 75% [7]) and the photodetector resolution. Compared to conventional scintillation crystals, noble liquids have similar or superior scintillation light yield (liquid argon: $\lesssim 51$ ph/keV [8], liquid xenon: ~ 40 ph/keV [9]), leading to an improved energy resolution. Furthermore, they are transparent to their own scintillation light and, unlike solid state detectors, degradation of the medium can be counteracted by continuously circulating the liquid through a purifier. Liquid xenon is commonly used due to its high density and scintillation light wavelength at 178 nm, offering a better stopping power than the other liquids and the possibility of detecting the light with cryogenic photomultipliers [10]. At lower light wavelengths, such as the peak of argon scintillation (~ 127 nm), wavelength shifters must be used to continue working with PMTs [11]. However, liquid argon is the ideal medium due to its very low cost, although alternative light read-out methods are required to avoid the granularity limitations imposed by PMTs and the efficiency loss introduced by wavelength shifters.

Position sensitive Gaseous Photomultipliers (GPMs) can be manufactured with large active areas and with photocathodes sensitive to UV noble liquid scintillation light, offering a cheap alternative to vacuum and solid state photon detectors and with a position resolution on the order of 100 μm . Hole-type micropatterned structures like Thick Gaseous Electron Multipliers (THGEMs) are indispensable components in such GPMs. When arranged in a cascade, with the first structure coated with a thin film of photosensitive material and operated at high voltages immersed in a noble gas, they focus the photoelectrons into the holes and provide additional electrons and positive ions via collisions with the gas atoms. The cascaded structure allows for lower individual operating

voltages and discharge probability while increasing the detector gain. Caesium Iodide (CsI) can be used to form a reflective photocathode [12], with sensitivity to UV light below the 220 nm threshold with a quantum efficiency from $\sim 15\%$ for liquid xenon scintillation (178 nm) to $> 60\%$ for liquid argon scintillation light (127 nm) (see Figures 7 and 8 in [13]) and a time resolution < 10 ns [14–16].

The stability of position sensitive GPMs at cryogenic temperatures down to 88 K has been tested with positive results [17], confirming the expected reduction in photoelectron extraction efficiency with increased gas density at low temperatures. Liquid xenon scintillation light detection has also been performed with a GPM detector [18]. In this article the construction, operation and testing of a prototype GPM intended for liquid argon scintillation light is presented. Voltage settings are optimised at room temperature to maximise the gain, and the position resolution is studied. Further tests towards the operation of the detector submerged in liquid argon are also carried out: structural tests in liquid Nitrogen, room temperature multiple-photon position reconstruction and gain stability.

2. GPM Detector Design and Operation Principle

The detector used in this work is shown in Figure 1a. The design comprises three micropatterned structures housed in an aluminium cylinder of 10 cm diameter and 10 cm height, with a 3 mm thick circular window on one end and two diametrically opposed gas inlet/outlet perforations on the other. A stainless steel CF flange with nickel pins is used for signal and power feedthrough, with all structural components vacuum-sealed with Teflon gaskets. The window material is Mag-

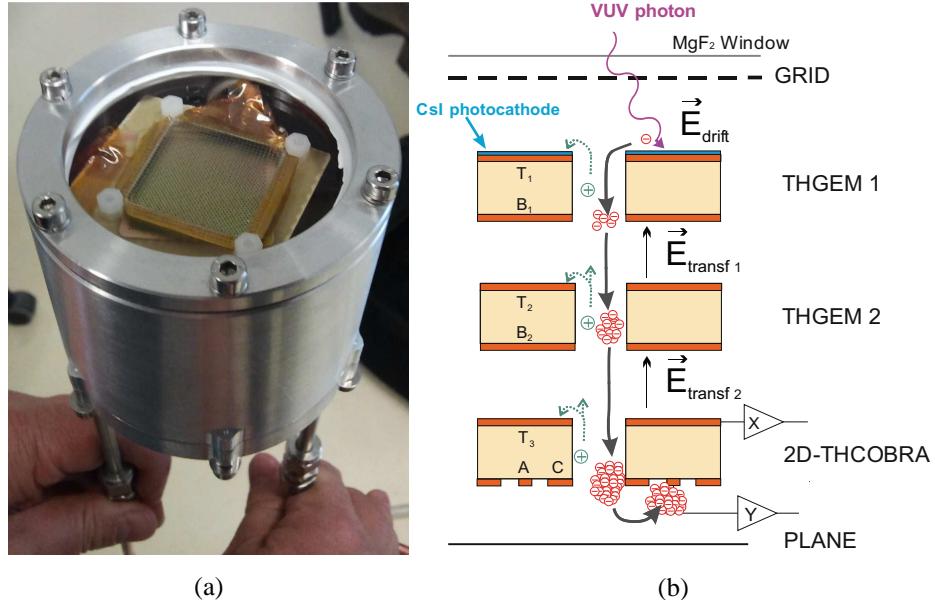


Figure 1: (a) Detector prototype - the MgF₂ window, vacuum-sealed with Teflon gaskets to the aluminium cylinder, the grid and the first THGEM are visible, (b) schematic representation of the detector and its operation principle.

nesium Fluoride (MgF_2) due to the high typical transmittance in the VUV range ($T > 50\%$ at 121 nm [19]). The three micro-structures comprise two THGEMs and a 2D-THCOBRA, copper-cladded 400 μm thick G10 sheets with 400 μm holes mechanically drilled, without rim and with 800 μm pitch in the case of the THGEMs and with an 80 μm rim and a 1 mm pitch in the case of the 2D-THCOBRA. Strips 100 μm wide were etched on the top and bottom surfaces of the 2D-THCOBRA following a photolithography process, and these are joined by resistive lines deposited by serigraphy (see Figure 1 in [12]). The detector is operated in flow mode with a gas mixture of 95% Neon and 5% CH_4 that fills the inside of the cylinder and serves as multiplication medium. As shown in Figure 1b, a VUV photon that enters through the MgF_2 window and interacts in the CsI photocathode deposited on top of the first THGEM may produce emission of a photoelectron with a certain probability. The photoelectron drifts due to the electric field between the THGEM top and bottom surfaces (T_1, B_1) into the THGEM holes. As it accelerates in the gas medium, collisions with Neon atoms start an electron multiplication process. The electron cloud extracted from the first THGEM holes drifts towards the second THGEM due to the transfer field $\vec{E}_{\text{transf}1}$. A second multiplication occurs in the second THGEM and the electron cloud then drifts towards the 2D-THCOBRA in $\vec{E}_{\text{transf}2}$. A bias voltage V_{CT} is applied between the top strips (T_3) and the cathode (C) on the bottom of the structure, generating a field in which the electron cloud accelerates and multiplies. Further multiplication occurs due to the voltage V_{AC} between the cathode and the anode strips (A), where the signal is collected and divided. An opposite sign signal is induced in the top strips [12], allowing for 2D reconstruction of the position of incidence of the VUV photon.

3. Experimental Setup and Methods

Detector gain measurements and image acquisition are performed simultaneously at room temperature. For all measurements, a collimated Hg(Ar) lamp is used to provide the VUV photons producing the signals. The signals from the top and anode resistive lines in the 2D-THCOBRA are preamplified with a Cremat CR-111 and digitized with a CAEN N1728B NIM ADC module (4 channels, 14 bits, 100 MHz sampling rate) and the image is reconstructed by weighting the integrated signals from each end of the resistive lines following the principle of resistive charge division [20].

The single photoelectron energy distribution is well modelled by a Polya distribution (see e.g. [21]) of the form

$$P_m(g) = \frac{m^m}{\Gamma(m)} \frac{1}{G} \left(\frac{g}{G}\right)^{m-1} e^{-m\frac{g}{G}} \quad (3.1)$$

where g is the energy, m a dimensionless real parameter and G the detector Gain. In log scale the function has a linear component of the form

$$\log(P_m(g)) \sim m \frac{g}{G} + \dots \quad (3.2)$$

Relative gain comparisons can be performed using the inverse slope of the linear part of the distribution [22–24].

To measure the photoelectron collection efficiency of the detector, one end of the anode-strip resistive line is disconnected, so that all the charge flows to the other end. After preamplification,

the signal is amplified with a Canberra 2022 (shaping time 2 μ s, $G = 100$ and $G_f = 1$) and then digitized using an Amptek MCA8000A.

4. Results: detector characterisation

To achieve optimal performance, the detector must hold its structural integrity at liquid argon temperatures and retain a stable and predictable gain. Due to the nature of the liquid argon scintillation light, the detector has to detect simultaneous multiple photon interactions. In this section, measurements to determine the detector performance are presented. First, measurements to characterise the GPM behaviour are performed at room temperature: gain, photoelectron collection efficiency and position resolution, and finally, preliminary tests to evaluate the detector behaviour under simulated liquid argon conditions are carried out: multiphoton position reconstruction, gain stability and evolution and detector structural integrity tests at cryogenic temperatures.

The detector gain was measured at room temperature as a function of the two 2D-THCOBRA potentials, V_{AC} and V_{CT} , with the potentials on THGEM1 and THGEM2 fixed at 595 V and 550 V respectively, empirically chosen as a compromise between efficiency and discharge probability, and the transfer fields set to $E_{\text{transf} 1} = E_{\text{transf} 2} = 300 \text{ V/cm}$. The gain as a function of the Anode

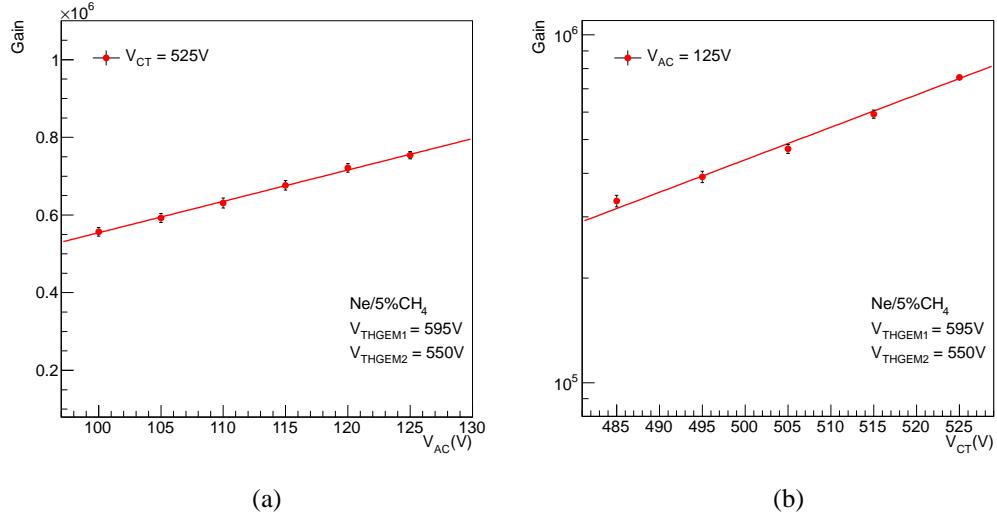


Figure 2: Detector gain as a function of the Anode strips–Cathodes potential (a), and as a function of Top strips–Cathodes potential (b), in number of collected electrons per photoelectron.

strips–Cathode potential V_{AC} is shown in Figure 2a for V_{AC} from 100 V to 125 V in steps of 5 V and for Cathodes–Top strips potential fixed at $V_{CT} = 525 \text{ V}$. The behaviour observed in this region is approximately linear, indicating that no additional electron multiplication occurs in the gas at this stage. In Figure 2b, gain measurements as a function of V_{CT} are presented. V_{CT} is varied from 485 V to 525 V in steps of 10 V for a constant $V_{AC} = 125 \text{ V}$. In this range, the observed variation has an exponential behaviour, as there is electron multiplication taking place in the 2D-THCOBRA holes, between the top strips and the cathodes. Based on this study, optimal operation voltages

were chosen ($V_{AC} = 125$ V and $V_{CT} = 525$ V), corresponding to a gain of $G = 8 \cdot 10^5$. For these values, detector operation is stable and there is a low discharge rate.

The drift field between the first THGEM and the grid has a strong effect on the extraction of photoelectrons from the CsI surface. In Figure 3, the detector gain is plotted as a function of the drift potential with respect to the top of THGEM1, where it is shown that the gain falls

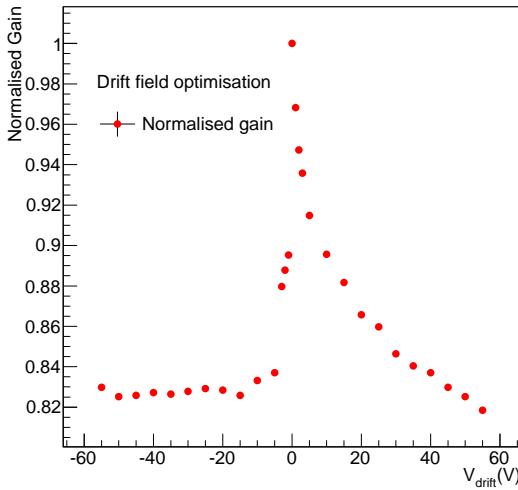


Figure 3: Detector gain as a function of drift potential

rapidly when applying a non-zero potential. A negative potential stops the photoelectrons from being extracted from the CsI layer and the gain flattens out at $\sim 83\%$ of the maximum for $V_{drift} \simeq -10$ V. However, with increasingly positive potential the extraction of photoelectrons is aided by the additional electric field, and the gain drops more slowly. The optimal value found was $V_{drift} = (0 \pm 0.5)$ V, so the grid potential was set to zero with respect to the first THGEM for the rest of the tests.

Maximising the detector collection efficiency (ratio of collected to extracted photoelectrons) is specially important when working in single-photoelectron mode. This ratio approaches 1 as V_{THGEM1} is increased, and to measure it the gain is kept approximately constant for different voltage settings by comparing a reasonably linear region of the energy spectra and applying equation 3.2. The comparison is performed by integrating this region to estimate the amount of collected charge for different THGEM1 potentials [25, 26]. The result is shown in Fig 4, where $\varepsilon_{coll} \sim 1$ at $V_{THGEM1} = 595$ V. At this bias voltage, the surface field between holes is high enough for the detector to reach an extraction efficiency higher than 70% [25].

To determine the GPM position resolution the edge spread function method was applied to one of the edges of the pattern created by the first THGEM in the image (see Figure 5). The result of the fit yields $< 90 \pm 30 \mu\text{m}$ in the direction of the anode strips and $90 \pm 30 \mu\text{m}$ in the direction of the top strips.

An experiment was set up to test the detector ability to reconstruct UV light from naturally occurring sources. Flame light below the CsI 220 nm threshold should be detectable by the GPM [27],

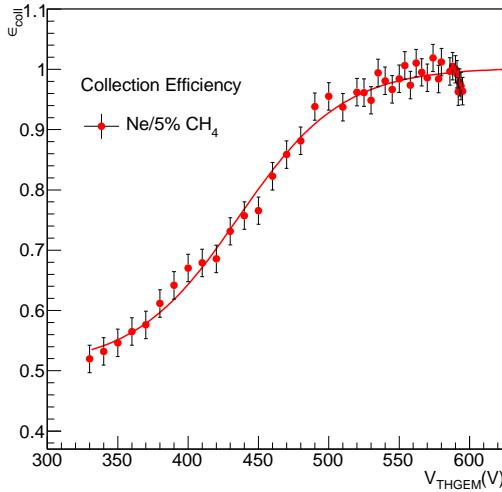


Figure 4: Photoelectron collection efficiency as a function of THGEM1 potential

so a lit candle was placed in front of the detector, collimated and attenuated with plastic film, as shown in Figure 6 (left). In the absence of attenuation, flame UV light overwhelmed the detector, causing discharges due to space-charge accumulation, confirming the hypothesis. With enough attenuation, it was possible to ensure that only single photons hit the detector. An image built after a 3 s exposure to candle light is shown in Figure 6 (right). A series of frames were recorded and a movie showing the movement of the UV light sources within the flame can be found in [28]. In combination with an IR detector, a 360° collimated GPM can be used for outdoor fire detection.

Liquid argon produces < 51000 scintillation photons per MeV of incident particle [8]. These photons can extract photoelectrons from the GPM CsI photocathode ($QE > 10\%$ [13]). Assuming that the detector is observing 0.511 MeV gamma-ray interactions in a cylinder of liquid argon of 10 cm height with a MgF₂ window (70 mm diameter), the number of photoelectrons generated is on the order of $\mathcal{O}(10^1) \sim \mathcal{O}(10^2)$. Therefore, the system must be able to reconstruct events with multiple photons that simultaneously produce photoelectrons in the photocathode.

To simulate argon emission, a spinning disk with a slit allows pulses of UV light from the Hg(Ar) lamp to be detected, being integrated for 10 μ s. The detector, operated at room temperature at 20 cm from the light source was moved from right to left in steps of ~ 2 cm to determine if the average position of the photon pulses would vary accordingly. In Figure 7 three energy distributions and their corresponding position distributions are shown. The results show that the detector can simultaneously reconstruct the energy of multiple photons and their average position of arrival at the photocathode. The first measurement (violet energy distribution, position (a)) suffered from more noise from one of the channels, hiding most of the multiple photon signal due to pileup conditions. The trigger threshold was increased for the rest of the measurements. It is worth noting that when operated in multiphoton mode, the detector loses its single photon position capability (reconstructed always around the centre) due to the long integration time.

In order to test the stability of the gain during prolonged time periods, the GPM was set up

to detect single photons from the UV Hg(Ar) lamp. The experiment ran for approximately 44 h, collecting data in intervals of 3 min. The following variables were measured: anode and top-strips gain, pressure of the gas entering and leaving the detector, room temperature and instantaneous discharge times. The purely exponential part of the measured energy distributions for every 3 min interval was fitted to extract the gain. Every signal indicating a high current in the voltage supply (discharge) was recorded.

A standard Principal Component Analysis (PCA) reveals linear dependence between gains, room temperature and pressure of the gas leaving the detector. In Figure 8, the normalised pressure (green histogram) and temperature (blue histogram) are shown together with the gain from the anode strips channels (purple histogram), as a function of time¹. Discharges are shown as red points on the gain distribution. The ratio between top and anode strips gain is shown in Figure 9, stable at a value of $\sim 67\%$.

The variation in gain observed in Figure 8 is mainly due to the variation in room temperature and pressure and to occasional discharges, and can be described by:

$$\frac{dG}{dt} = \left. \frac{\partial G}{\partial p} \frac{dp}{dt} + \frac{\partial G}{\partial T} \frac{dT}{dt} + \frac{\partial G}{\partial t} \right|_{\text{discharge}} \quad (4.1)$$

Where the partial derivatives are calculated for all the other variables constant. Integrating this expression yields:

$$\begin{aligned} G(p(t), T(t), \text{disch}(t)) &= G_0 + \frac{\partial G}{\partial p} p(t) + \frac{\partial G}{\partial T} T(t) + G(\text{disch}(t)) \\ &= G_1(p(t)) + G_2(T(t)) + G_3(\text{disch}(t)) \end{aligned} \quad (4.2)$$

The behaviour of the gain with respect to pressure variations $G_1(p)$ was studied in regions of constant room temperature ($T = 297.1$ K). On average, a discharge occurred every 46 minutes, so it was required that no discharge occurred in the last 30 mins. A linear correlation between pressure and gain was established, with negative slope. Analogously, $G_2(T)$ was fitted and a positive slope was found. The discharge-dependent term is obtained by calculating $G_3(\text{disch}(t)) = G(p, T, \text{disch}) - G_1(p) - G_2(T)$. As shown in Figure 10, discharges are responsible for a $\pm 10\%$ variation around the mean at $(0 \pm 2)\%$.

Given the stable operation and multiple photon detection capabilities, preliminary structural tests at cryogenic temperatures were carried out. Initially, the MgF₂ window was substituted for a more robust aluminium window. The detector was then evacuated to a pressure of $\sim 10^{-6}$ mbar and then cooled down to 77 K with liquid Nitrogen. After reaching stability, the detector was removed from the liquid and was left to heat up to room temperature. During this stage, the pressure increased to 200 mbar, an encouraging result considering that the gas pressure will be kept at ~ 1 atm during normal operation. To further ensure structural integrity and good performance of the Teflon gaskets, an additional test was performed with a dummy glass window. argon was

¹Gain is normalised to an arbitrary central value (1200 ADC/e⁻). Pressure is normalised to the first measured value (1009.22 hPa) and temperature to the most common value (297.1 K). Pressure and temperature are then transformed as $1 + 100 \times (x - 1)$, and temperature is shifted down by 0.3 for illustration purposes. Time is normalised to the length of the experiment (145711 s or 40.48 h)

allowed to flow through the detector until all air had been removed. When the pressure reached 1.2 atm, all valves were shut and the detector was cooled down using liquid Nitrogen. The pressure was maintained at ~ 1.2 atm by adding more argon, since the gas freezes below 84 K. When equilibrium was reached, the liquid Nitrogen was removed and a block of solid argon was visible through the glass window of the detector. As the system warmed up to room temperature, the flow of escaping argon was regulated to keep the pressure constant. When the pressure dropped to 1 atm all valves were shut. No water, in liquid or solid state, was visible inside the detector volume or on the inner surface of the glass window after all the argon evaporated and the system reached room temperature. The detector was pumped down to 10^{-6} mbar to test the glass window strength, without problems. After turning off the pump the pressure did not go above 10 mbar, hence the system is vacuum tight with Teflon gaskets and a glass window, even after the process of cooling and heating. While in the actual prototype a MgF₂ window is used, there is no reason to expect a significant change with respect to the measurements performed with glass.

5. Conclusions

A new large area Gaseous Photomultiplier utilizing a cascade of Thick GEM layers intended for gamma-ray position reconstruction in liquid argon is proposed. A prototype designed to operate at cryogenic temperatures inside the liquid phase and to reconstruct liquid argon scintillation light was built. A number of performance measurements were carried out at room temperature and stable operation high-voltage settings: photoelectron collection efficiency, position resolution and stability. A photoelectron collection efficiency on the order of 1, a gain of $8 \cdot 10^5$ per photoelectron and a position resolution better than 100 μm were measured. Discharges were observed every 46 min of operation on average ($0.1 \text{ discharges}/(h \cdot \text{cm}^2)$). Detector gains were stable for the whole data taking period within $\pm 10\%$, showing a slow charging-up effect after every discharge. Gain variations due to pressure and temperature disappear when the two variables are under control in the laboratory. However, to reduce the discharge rate it is necessary to operate with lower bias settings, limiting the stability of the gain to the above-mentioned $\pm 10\%$.

The proposed detector has potential applications ranging from medical physics and engineering, to particle physics. Initial tests of robustness against cryogenic temperatures were performed successfully. The next essential step would be to demonstrate the operation of the Gaseous Photomultiplier inside the liquid argon phase.

Acknowledgments

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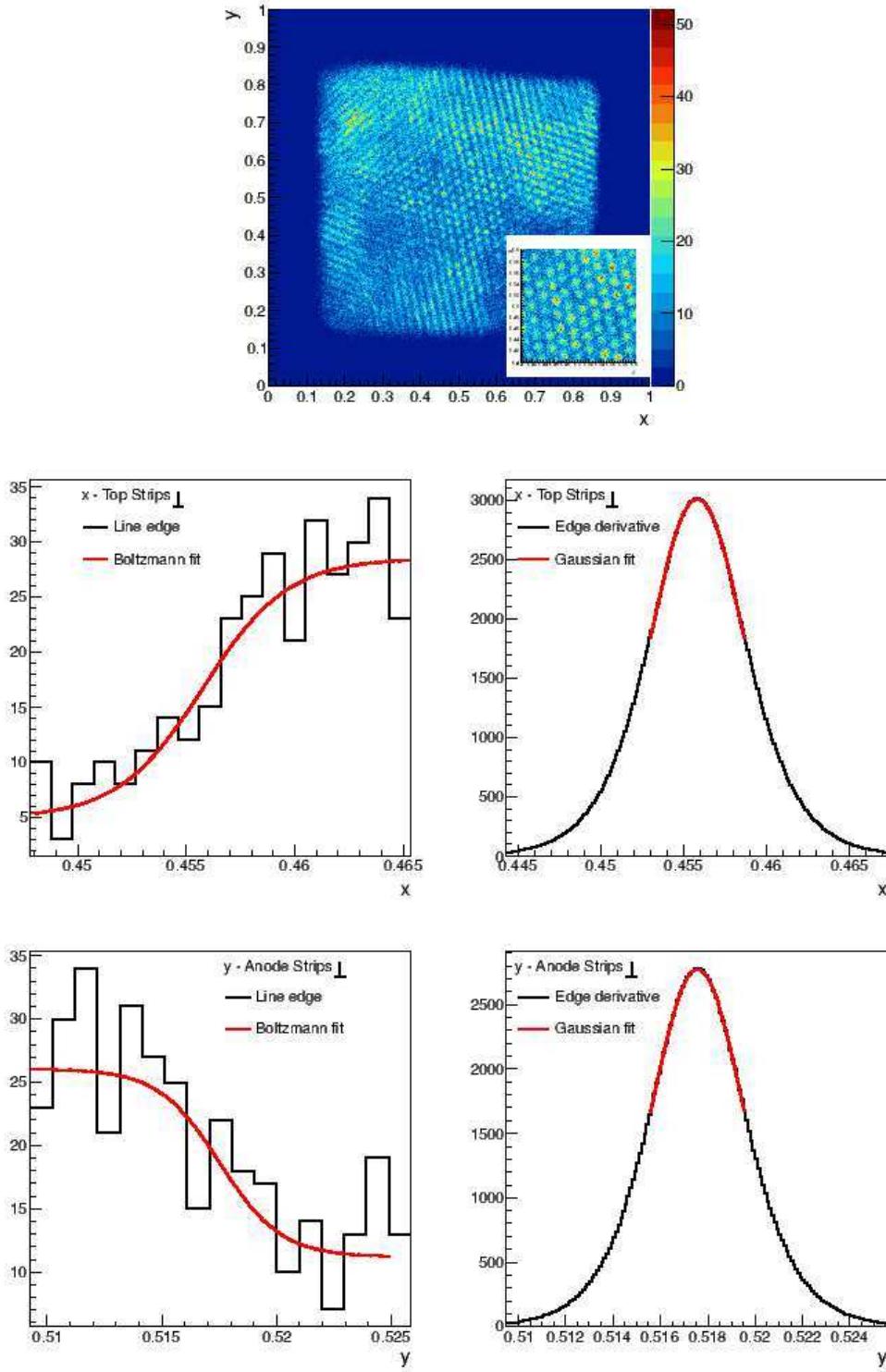


Figure 5: Position resolution measurement with the Line Spread Function method. The spread of one of the edges in the THGEM1 imaged pattern is fitted to a Boltzmann function. The derivative of the fit is taken and fitted to a gaussian to obtain the resolution. The results obtained are $\sigma = 90 \pm 30 \mu\text{m}$ in the x -direction (top strips) and $\sigma \lesssim 90 \pm 30 \mu\text{m}$ in the y -direction (anode strips). Scale: $3.12 \text{ cm} = 1$.

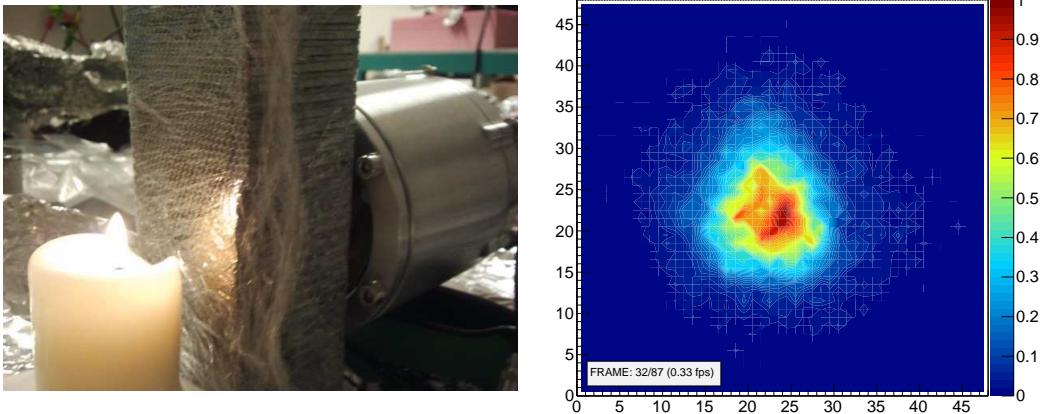


Figure 6: Experimental setup for candle tests. A lit candle in front of the GPM, UV radiation collimated and attenuated with plastic film (left). Example image obtained from a 3 s exposure time, showing the burning candle flame shape (right). A full animated sequence can be watched in [28]. Scale: 3.12 cm = 48px.

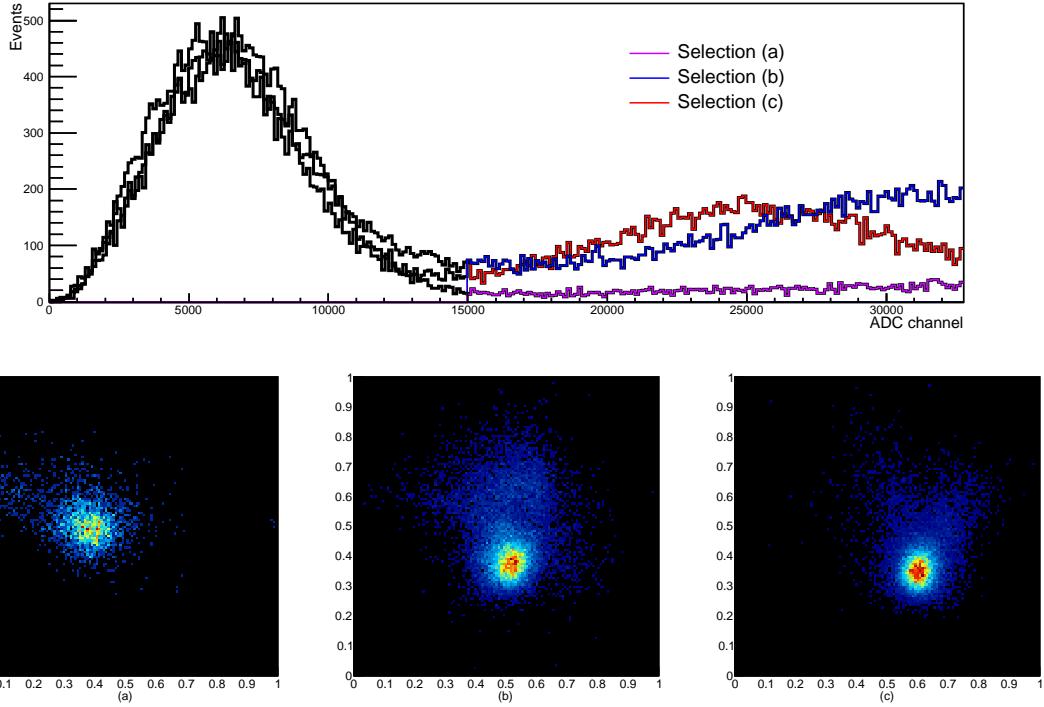


Figure 7: Displacement of average position and energy distribution of multiple photon interactions. The single-photon polya energy distribution is modified by multiple photon interactions appearing in the high end of the spectrum as a resonant peak, revealing the average energy deposited in the detector per multiphoton event. A different average number of simultaneous photons interact in the photocathode in cases (b) and (c), and hence their energy distributions do not peak at the same energy. The maximum number of available ADC channels was reached and the distributions cannot be fully shown. An excessive number of low-energy events during data-taking hides the multiphoton peak in (a) due to pileup. Scale: 3.12 cm = 1.

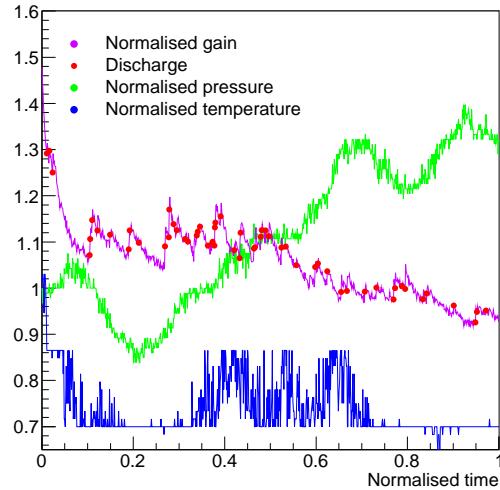


Figure 8: Normalised pressure (green histogram), temperature (blue histogram) and gain from the anode strips channels (purple histogram), as a function of time. Discharges are shown as red points on the gain distribution.

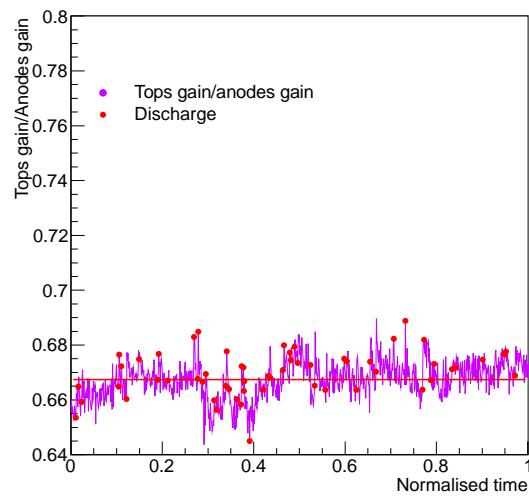


Figure 9: Ratio of the gain measured from the top strips signal to the gain measured from the anode strips signal. A stable value of $\sim 67\%$ is observed during operation.

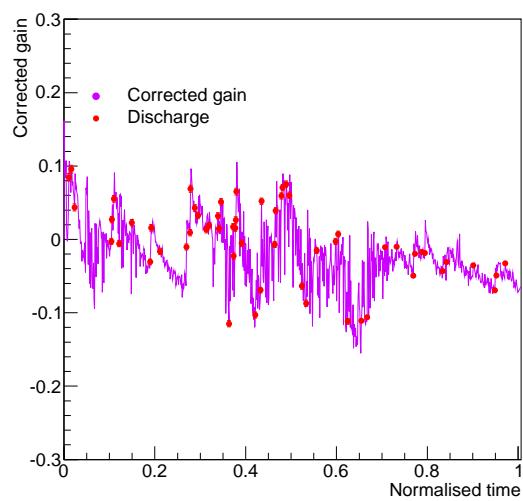


Figure 10: Gain evolution after correcting for the variation due to temperature and pressure. Discharges induce oscillations of $\pm 10\%$ around the mean.