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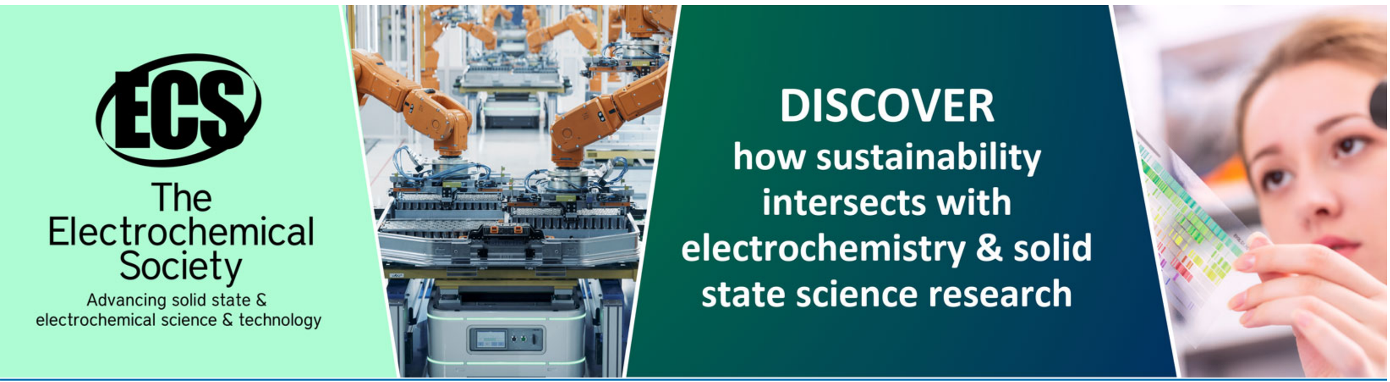

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Studying secondary discharges with an optically read out GEM

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Abstract. Gas Electron Multiplier (GEM) has become a commonly employed technology for modern high-rate particle and nuclear physics experiments. A key parameter for their long-term sustainability is stability against electrical discharges. Typically, these electrical breakdown events occur within the holes in the GEM foil, but they may also propagate into the gap between subsequent GEM foils resulting in secondary discharges. It is crucial to mitigate secondary discharges since they can result in irreparable damage to the detector. Accordingly, many successful methods have been developed to increase their stability against discharges. However, the propagation of discharges is still not fully understood. In this study, an optically read out GEM detector incorporating a sCMOS camera is developed as a new tool to investigate the formation of secondary discharges. We used optical imaging to capture the time evolution of the light from discharges. Studying the glow in instances leading and not leading to a secondary discharge, we pursue to determine the underlying mechanisms for discharge propagation.

1. Introduction

GEM (Gas Electron Multiplier) [1; 2] detectors are a type of gaseous ionization detectors implemented in various particle physics experiments such as COMPASS [3], TOTEM [4], CMS [5], ALICE [6] for detecting and tracking ionizing particles. The geometrical properties of GEMs provide great radiation hardness [7] and internal ion-backflow suppression [8], making them suitable for use as amplification stages in experiments with very high particle rates. GEM detectors incorporate 50 µm thick polyimide foil structures, with 5 µm thick copper claddings on both surfaces. Multiple holes with 50 µm diameters are etched on the foil. When a potential difference is applied between the two sides of a foil, the geometrical structure of the holes enables high fields inside the hole. This leads to avalanche multiplication of electrons drifting towards the foil.

1.1. Discharges in GEM detectors

One of the limiting factors for the long-term stable high gain operation of GEMs is the occurrence of electrical discharges. These break-down events cause the gain in the GEM holes to momentarily drop resulting in short-term blindness of the detector. Furthermore, discharges with higher energies might irreparably damage the delicate GEM foils, requiring the replacement of the involved structures. Because of the problems involved with GEM discharges, there has been extensive research throughout recent years aiming to understand and mitigate them.

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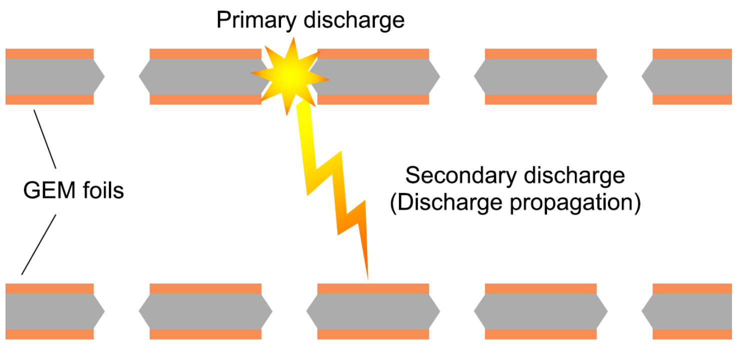

Figure 1. Schematic of the two types of GEM discharges.

We discuss two types of discharges occuring in GEMs. These are primary and secondary (propagated) discharges. Primary discharges are sparks occuring in GEM holes. They appear when the number of charges inside a given hole exceeds a certain limit ($Q_{crit} \approx 10^6$-10^7 electrons), comparable to the Raether limit in proportional chambers [9]. The underlying mechanisms leading to primary discharges have been intensively studied and are generally deemed to be understood [10].

Under certain conditions primary discharges were also observed to propagate into a transfer gap (between consequent GEM foils in a stack as suggested by Figure 1) or induction gap (between GEM foil and the anode). These propagation events, termed secondary discharges, are generally more dangerous for the detector given they depose higher energy to the involved foil and the read-out electronics. They occur when a high field is applied across the corresponding transfer or induction gap under the discharging GEM foil. Secondary discharges are always observed as a follow up to a primary discharge, however the delay between the two events can vary between instantaneous to tens of microseconds. This fact makes it difficult to pinpoint what physical mechanisms are involved in the propagation phenomenon. Currently, a notable theory attributes the formation of delayed secondary discharges to the heat generated by the initial primary discharge. According to this approach the work function of the bottom copper electrode on the foil is reduced as it is heated up by the primary discharge [11; 12]. This allows the thermionic emission of electrons given a strong applied induction field. The resulting current leads to the discharge propagation. It has also been shown that by changing various RC properties of the detector HV scheme the probability of secondary discharge occurrence can be significantly reduced [13].

A more recent approach aiming to discover new clues in solving this mystery has been to use optically read out GEM detectors and high speed imaging (up to 1 million frames per second) [12]. By capturing detailed images of the area around GEM holes after primary discharges within the time frame leading to propagations it is aimed to provide a new perspective onto the evolution of this complicated phenomenon.

2. Setup and methods

The aim of the conducted measurements is to study GEM discharges by analysing the intensity of the light emitted during and after the initial spark. For this task, an optically read out GEM detector, which is common and well established in applied physics [14; 15], is used. For the optical read-out an Andor Zyla sCMOS camera [16] and a Retiga R6 CCD camera[17] are used because of their great low-light performance and high spatial resolution to capture detailed images of GEM discharges. The measured light intensities from the two used cameras are

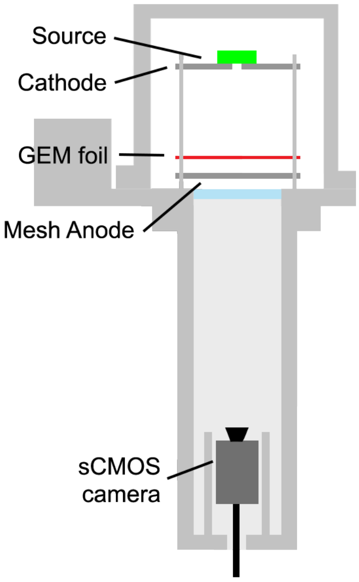

Figure 2. Sketch of the detector setup.

Figure 3. Photo of the detector setup.

compared to tackle the problem of camera specific signal responses. In each case, the cameras are placed inside a light-tight vessel attached to a multi-purpose GEM detector chamber that is modified to be used in this optical approach. To achieve a line of sight into the gas volume, a BOROFLOAT® window is incorporated on one side of the GEM chamber. In a similar fashion, a mesh is used as the anode electrode to avoid obstructing the view of the camera to the GEM holes. The used GEM detector incorporates a single 140 µm pitch GEM foil and is operated with a drift gap of 39 mm and an induction gap of 2 mm. The detector is flushed with multiple gas mixtures for the studies, which include Ar-CO_2 (90-10) Ne-CO_2 (90-10) and Ar-CF_4 (90-10). The drift volume is irradiated using a mixed alpha ^{239}Pu–^{241}Am–^{244}Cm source [18] with a rate of ∼500 Hz.

The optical imaging capabilities of the setup are tested in various ways prior to studying GEM discharges. A requirement for the comprehensive discharge studies is to be able to distinguish between individual GEM holes on the foil within the captured images. Hence, to test the spatial resolution capabilities of the camera, multiple images of discharges are captured and then combined. In these combined images it is possible to recognize and distinguish discharges inside neighbouring GEM holes and the hexagonal hole pattern of the foil (see Fig.4). With this, the resolution achievable with the setup is deemed to be acceptable.

In previous approaches on optical GEM discharge studies, the means to determine the time evolution of the emitted light is to use a high-speed camera to capture the progression of the discharge light with multiple images [12]. Although this approach enables very high precision and consistency, it requires very expensive imaging equipment which are not easily accessible for long term systematic studies. For the following conducted measurements, the used cameras don't support high speed acquisitions as they are limited to a frame rate of maximum 100 Hz for the used sCMOS and 7.1 Hz for the CCD cameras. Therefore, using the direct approach to analyse the time evolution of a single discharge propagation by capturing multiple images of it isn't possible. However, by using a specific triggering scheme to dictate when the camera starts

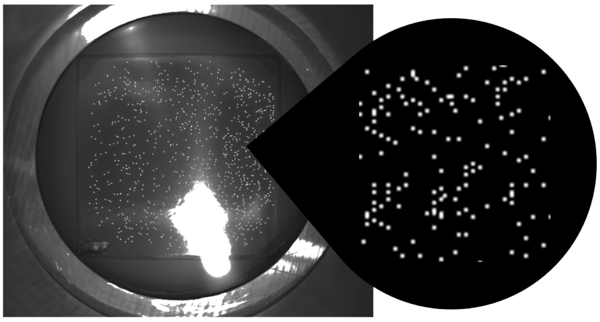

Figure 4. Combined image of multiple primary discharges with a close up on a section of the foil. Dsischarges in neighbouring holes can be distinguished and the hexagonal hole pattern can be recognised.

the exposition of each captured image, it is possible to reconstruct the evolution of discharges.

For controlling the exact time the cameras start their exposure, the electrical signal induced by the primary discharge is measured at the anode and is used as a trigger signal to start exposing the imaging sensor. By adding an adjustable delay between the instance when the discharge occurs and when the trigger signal is sent, it is possible to capture images at certain timestamps after a discharge. Using these images recorded at different stages of a discharge it is possible to study its evolution frame by frame without needing a high-speed camera. To tackle the problem that discharges can display a variety of energy depositions, multiple discharges were captured for any given timestamp and the observed brightness values were averaged including an error. The absolute timestamp for a given image is recorded by using the signal sent by the camera regarding the start of the sensor exposure. The response times to the sent trigger signal are measured to be (15 ± 5) µs for the sCMOS camera and (60 ± 1) µs for the CCD camera.

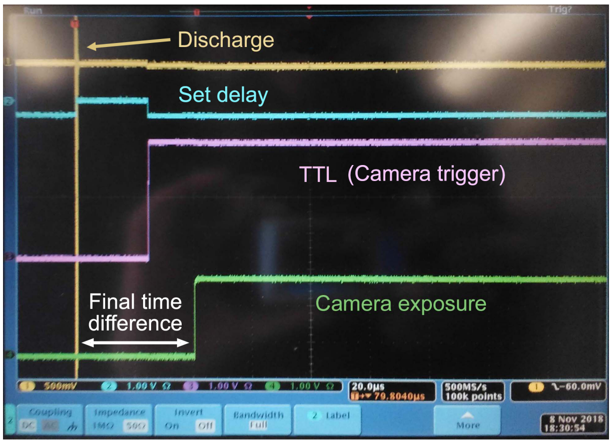

Figure 5. The signals used for the triggering of the camera. Yellow: The electrical signal induced by the primary discharge measured at the anode. Blue: Adjustable delay to control the time difference between camera exposure and discharge. Purple: The trigger sent to the camera. Green: Gate from the camera showing the exposure of the sensor.

However, there are two main shortcomings of using an indirect approach for reconstructing the time evolution of glow intensity. Firstly, as the used camera is not fast enough to capture

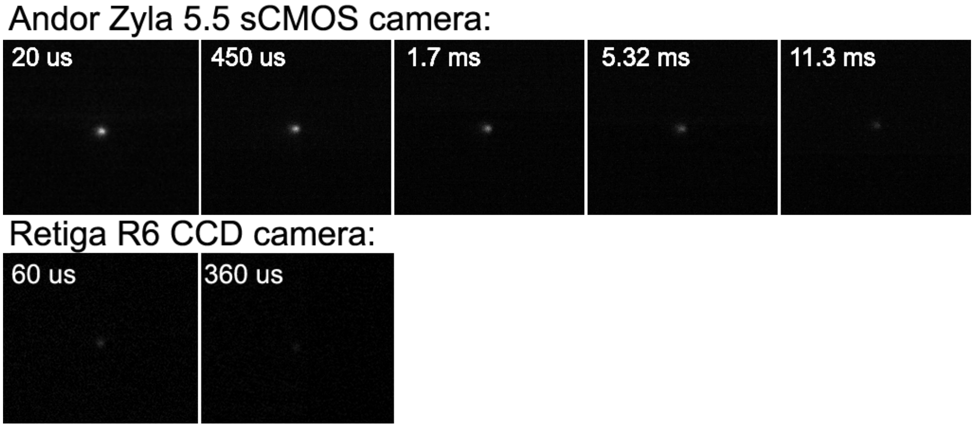

Figure 6. The observed time evolution of the glow after a primary discharge compared between two use scientific cameras. Given time information is for the initial signal peak from the primary discharge being in time 0.

the frame by frame time evolution of a single event, multiple discharge events are needed to be studied to produce a mean brightness value for each time frame. Secondly, if the high-light robustness of the used imaging sensor is lacking, the measured light intensity values can be corrupted and inaccurate. For measurements concerning rapid events such as discharges, scientific cameras with short exposure imaging capabilities are required. In general, such devices incorporate electronic shuttering. Nonetheless, this design results in the used sensor getting slightly exposed by bright light sources even during the "closed" shutter stage prior to imaging. Which in turn leads to inaccuracies in the measured glow evolution. For example, for the conducted study on GEM discharges, two different cameras with distinct imaging sensor architectures (CMOS and CCD) are compared. The used cameras result in vastly different evolution timescales for the observed prolonged glow after primary discharges (see Fig.6). This difference is thought to be caused by the cameras being affected by the initial high intensity light emission of the discharge to different extends. As a result, it is not possible to make any conclusions concerning the absolute lifetime of the glow without thorough profiling of the used cameras. Still, images captured with the same camera share the mentioned effect to the same degree. With this, it is possible to qualitatively compare the measured profiles acquired with the same camera. For the shown measurements the Retiga CCD camera [17] is used to capture the glow time evolution. The camera with the CCD imaging sensor was opted over the sCMOS based camera for the studies given its better performance in terms of the described high-light robustness.

3. Measurements and results

In general, discharges in GEMs are short duration events, with the involved discharge currents being quenched after only a few micro seconds. Still, a glow is observed around discharging GEM holes that can last up to 40 us after the initial event [12]. This prolonged glow is of great interest as it can be used to probe to the thermal activity following GEM discharges. It is believed that the thermal activity around a discharging GEM hole can be one of the factors leading to the delayed secondary discharge formation. For this reason, the conducted measurements aim to study and profile how the time evolution of glow light emission depends on various detector parameters.

Secondary discharge formation is known to be strongly related to the applied induction field

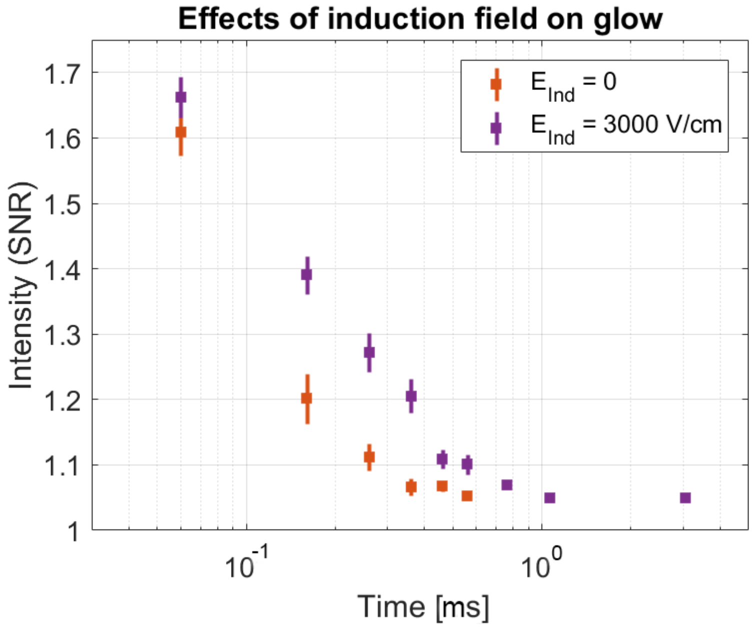

Figure 7. The observed glow evolution for Ar-CO_2 (90-10) using Retiga CCD camera. The measurements are conducted with 0 and 3000 V/cm applied induction fields, with the latter being close to the required field strength to produce propagations.

[11]. In order to establish a connection between the observed prolonged discharge glow and secondary discharge formation, the emitted light intensity is studied firstly as a function of the applied induction field (Fig. 7). The measure for the observed light intensity in the given figure is in the form of a signal to noise ratio. Here the noise is taken as the mean pixel value from a completely dark image captured with the setup. This value is dominated by the intrinsic electrical noise of the used sensor and the exposure of the captured dark image is made sure to be completely shielded against light leakages through the detector chamber. The signal counterpart is calculated as the mean value of a 3x3 pixel grid centred around the brightest point in the image. The use of a pixel grid is done to integrate over the area the GEM hole makes up on the captured images.

In Figure 7 it can be recognized that the observed glow intensity is stronger with higher applied induction field. Both shown induction field values are not high enough to lead to secondary discharge formation in the used gas, however the higher field value is very close to the onset field strength needed to produce secondaries. Operating in this region is important to make sure the measured light intensity values are not affected by any additional emissions from consequent secondary discharge events. The fact that higher activity around the GEM hole can be observed with increased induction field even in cases that don't necessarily lead to the formation of secondary discharges is perceived to be a new clue. This observation coincides with the theory that a streamer mechanism can be the initial step can escalate to a secondary discharge given the right condition. The streamer formed during the primary discharge in the hole can be expected to get ejected towards the anode given the applied induction field underneath the foil but doesn't necessarily evolve into a secondary discharge if the field is not strong enough. This displaced activity in turn results in increased light emission on the under side of the GEM hole that would be impossible to detect solely using the means of the induced electronic signals.

4. Conclusion and outlook

The shown studies indicate that an optical approach to investigate GEM discharges can offer new clues towards understanding the formation of secondary discharges. In this effort very high-end imaging equipment not commonly available in gas detector research facilities are shown to not be necessary. It is hoped that the developed measurement methods incorporating more accessible scientific camera options can motivate the further pursue of optical discharge studies.

In the conducted measurements the region around the GEM hole is observed to glow for a prolonged duration after primary discharges. This long lifetime light emission is shown to increase when a field is applied between the discharging GEM foil and the consequent anode electrode. However, the achieved preliminary results using the introduced techniques albeit promising are currently lacking in precision to make decisive conclusions concerning the correlation between the increased activity around discharging GEM holes and secondary discharge formation. For further measurements our aim is to mitigate the issue of image corruption by the initial bright light from the primary discharge. We plan to study secondary discharge formation from the side (through the gap between the GEM foil and the anode electrode) as to not face the primary discharges head-on. This is hoped to result in the performed absolute glow lifetime measurements to not be corrupted by the properties of the cameras.

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