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TECHNICAL REPORT

Optical readout studies of the Thick-COBRA gaseous detector

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ABSTRACT: The performance of a Thick-COBRA (THCOBRA) gaseous detector is studied using an optical readout technique. The operation principle of this device is described, highlighting its operation in a gas mixture of Ar/CF₄ (80/20 %) for visible scintillation light emission. The contributions to the total gain from the holes and the anode strips as a function of the applied bias voltage were visualized. The preservation of spatial information from the initial ionizations was demonstrated by analyzing the light emission from 5.9 keV X-rays of an ⁵⁵Fe source. The observed non-uniformity of the scintillation light from the holes supports the claim of a space localization accuracy better than the pitch of the holes. The acquired images were used to identify weak points and sources of instabilities in view of the development of new optimized structures.

KEYWORDS: Gaseous detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Charge transport and multiplication in gas; Electron multipliers (gas)

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1 Introduction

In recent years, the optical readout of scintillation light emitted during avalanche multiplication has been widely used as a readout modality for Micro-Patterns Gaseous Detectors (MPGDs). Stable operation at large gas gains in Gas Electron Multiplier (GEM) [1] and Micromegas [2], as well as the discovery of gas mixtures with high scintillation light yield in the visible wavelength region have made optical readout more accessible with the use of recent developments of high performance digital imaging sensors. Advances in commercially available cameras with high-resolution and low-noise sensors have allowed for unprecedented image quality and sensitivity, making optical readout an attractive readout modality for gaseous radiation detectors.

This powerful technique was previously employed for the studies of avalanches in Thick GEMs (THGEMs) [3]. An asymmetry of the avalanche propagation within holes has been reported and the multiplicity of holes involved in avalanches was studied. Similar observations, will be reported herein, corroborating this asymmetry.

The Thick-COBRA gaseous detector, hereafter THCOBRA [4], was studied using optical readout to examine and visualize its operation, in a similar manner as in the above mentioned study with THGEMs. This detector is based on the GEM operation principles and can be described as a hybrid amplification structure combining a THGEM [5, 6] and a Micro-Strip Gaseous Counter (MSGC) [7]. As such, it is an evolution of the Micro-Hole Strip Plate (MHSP) [8] using a more robust substrate. It has electrodes on the top and bottom sides of a thick substrate. The bottom electrode is segmented to feature thin anode strips in between the GEM holes.

Combining state-of-the-art imaging sensors with MPGDs operated in well-understood scintillating gas mixtures [9], it is possible to study in detail their performance and operation principles [10]. Stable operation of multi-stage amplification structures at large gas gains together with an optical readout have been successfully implemented for particle tracking with GEMs [11] and in

GEM-based TPCs [12–14] achieving good image quality in terms of high signal to noise ratio for particles interacting in their sensitive volumes.

In the present study, the operation concept of the THCOBRA detector was visualized by optical readout:

- Light and charge measurements, in order to visualize sharing between the THGEM and the MSGC-like structures.
- Corroborate in light-collection mode, the preservation of the primary ionization position information already observed in charge-collection mode [15].
- Localize weak spots of the THCOBRA electrodes' geometry causing instabilities, in order to improve its design.

2 Description of THCOBRA and principle of operation

In the figure 1, a picture of the THCOBRA foil with its electrodes' pattern on the bottom and top sides [16] is shown.

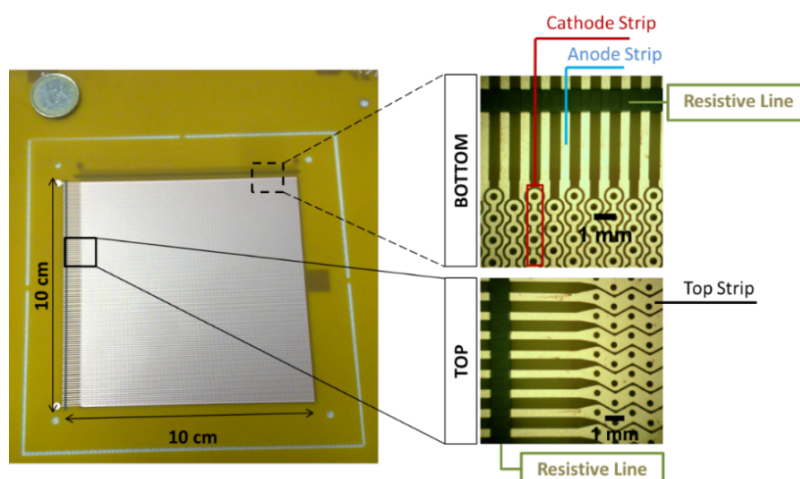


Figure 1. THCOBRA layout. View of the foil on the left. Bottom and top electrodes on the right. The upper-right picture displays cathode strips around the holes and anode strips in-between the holes. The top electrode (bottom-right) has segmented strips hereafter called top contacts.

The foil with an area of $10 \times 10 \text{ cm}^2$ was manufactured on a printed circuit G10 board with a thickness of $400 \mu\text{m}$ and was clad with $50 \mu\text{m}$ thick copper strips on both sides. The top electrode has strips of $400 \mu\text{m}$ width, while the bottom side has cathode strips of $200 \mu\text{m}$ width around the holes and anode strips of varying widths between holes. The diameter of the holes is $300 \mu\text{m}$ with a pitch of 1 mm . The principle of operation of the THCOBRA foil is based on two amplification stages (figure 2) [17]. This hybrid gaseous electron multiplier works as a THGEM inside the holes and as a MSGC-like structure between cathode and anode strips.

To operate the structure, a voltage difference between the top contact and the cathode is applied to create a high electric field inside the holes as is the case for THGEMs. In addition, between the

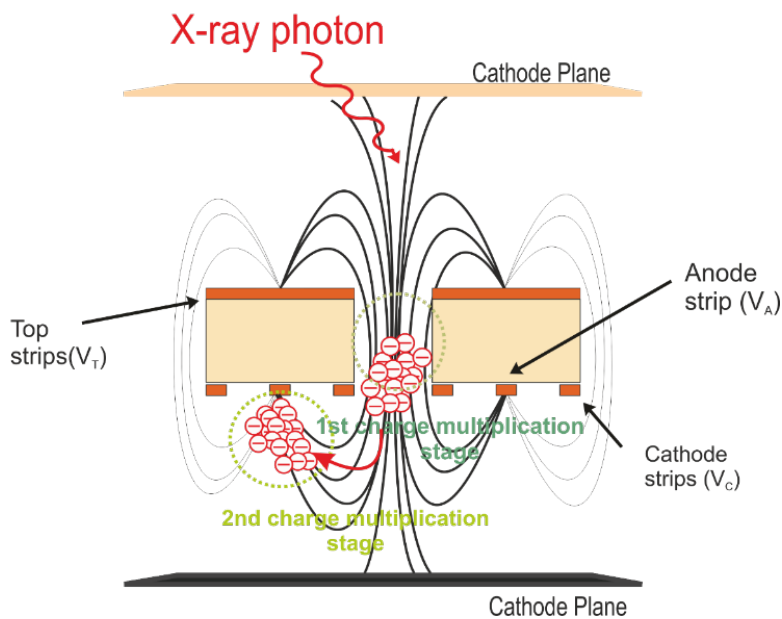


Figure 2. The operation principle of THCOBRA foil is based on a two-stage amplification structure, where the first amplification occurs within the holes and the second one near the anode strips.

anode and cathode strips a voltage difference is applied as in a MSGC to create a high electric field at the anode strips and add its contribution to the total gas gain.

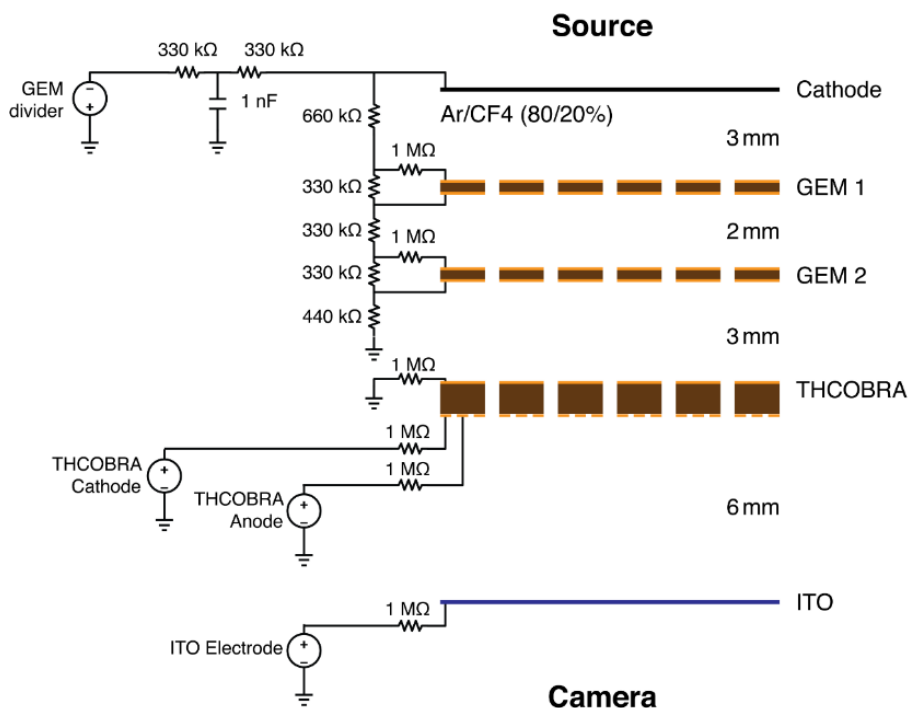


Figure 3. Schematics of the detector. A THCOBRA foil, a double-GEM stack, a cathode (on top) and an ITO electrode (on bottom) make up the optically read out detector.

3 Experimental setup

The detector used in this study consists of a double GEM stack (two standard thin GEM foils) on top of the THCOBRA foil, which is used as a pre-amplification stage to achieve higher gas gain. On the source side, a copper cathode foil is used to create a drift field in the 3 mm thick conversion gap. A camera was placed outside of the gas volume facing the bottom of the THCOBRA foil through a glass plate coated with 25 nm thick Indium-Tin Oxide (ITO). This ITO electrode is electrically conductive and has an optical transparency of approximately 80 % in the visible wavelength region.

The detector was powered as shown in figure 3 using multiple independent high voltage lines, with one of them connected to a passive divider for biasing the double-GEM stack. The top electrode of the THCOBRA was grounded and two high voltage lines were used to bias the bottom electrodes: one for the cathode and another one for the anode. This allowed for independent control of the two amplification stages of the hybrid structure.

An Ar/CF₄ gas mixture with volume concentrations of 80 % and 20 %, respectively, was used for the present study. This allows to have the initial interaction dominated by Ar atoms, while the CF₄ acts as a quencher and provides visible scintillation light emission. The scintillation light emission spectrum for this mixture features wide emission bands at Ultraviolet (UV) and visible wavelengths, which are attributed to CF₄ [9]. The light emission spectrum matches well the quantum efficiency of conventional Charge-Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) imaging sensors. In addition, the broad emission lines of the scintillation spectrum also contain atomic emission lines in the near-infrared range attributed to Ar [18].

In figure 4 the experimental setup is shown with the THCOBRA detector in between an X-ray generator and the CCD camera. The distance between the camera and the detector is determined by the focal distance of the optical readout system. Supplementary lenses were added to reduce the minimum object distance. In the present setup, the minimum object distance is approximately 8 cm for a lens with 50mm focal length and additional collimating lenses. The cameras used for these tests were an Electron Multiplying Charge-Coupled Device (EM-CCD), and a 6-megapixel CCD camera for high resolution studies.¹

4 Measurement results

4.1 Contributions from amplification stages

The light emission from the two amplification stages of the THCOBRA foil was visualized as a function of the applied bias voltages. The foil was biased by increasing the voltage difference across the holes up to the maximum achievable value in stable conditions. This was done by keeping the cathode and anode located at the bottom of the THCOBRA foil at the same potential. Figure 5 shows the powering scheme used for the measurement.

The top contact and the cathode (in figure 5.) were connected to separated high voltage lines and the currents were monitored. Similarly, the anode strips were biased and monitored independently. The measured currents are presented in figure 6.

¹The high-resolution camera was the QImaging Retiga R6 [19] which featured a $12.5 \times 10 \text{ mm}^2$ imaging sensor with 6M pixels of $4.54 \times 4.54 \mu\text{m}^2$. For high sensitivity measurements an ImagEM X2 [20] EMCCD camera was used featuring an image sensor of $8.19 \times 8.19 \text{ mm}^2$ with 512×512 pixels of $16 \times 16 \mu\text{m}^2$.

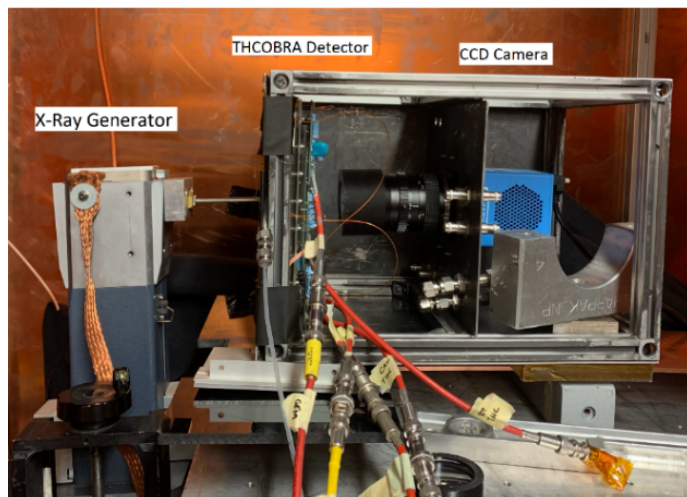


Figure 4. Experimental setup consisting of an X-ray generator, the THCOBRA gaseous detector and a high-resolution CCD camera.

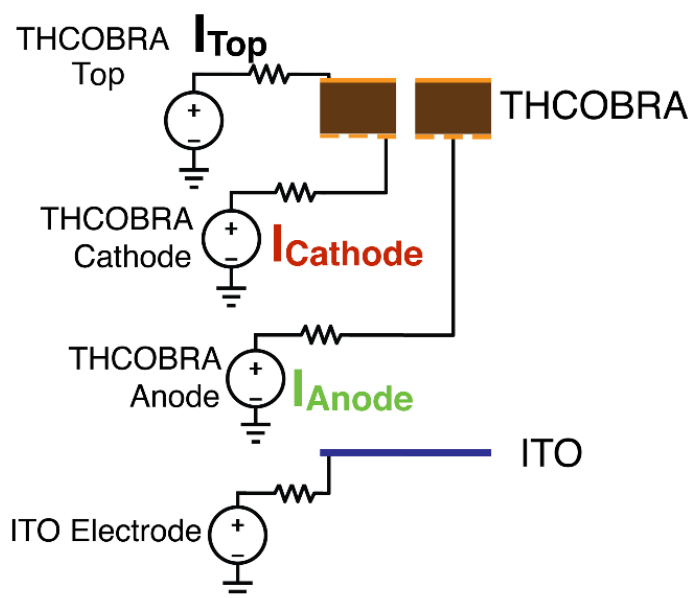


Figure 5. Schematics of the measurement setup for the visualization of the light sharing between the two amplification stages of the THCOBRA.

At zero voltage difference between anode strips and the cathode ($V_{AC} = 0$ V), the multiplication occurs only in the holes and creates a small currents: on the cathode (from the arrival of electrons) and on the top strips (from the arrival of the ions). By increasing V_{AC} , a negative polarity current at the anode starts to increase, produced by the further arrival of electrons. However, a change of polarity occurs in the current at the cathode due to the increased arrival of ions. As it shows one of the main features of the THCOBRA as an ion suppression amplification stage.

This overall effect on the currents indicates the onset of amplification from both stages and their contributions to the total gas gain. In addition to the current measurements explained above,

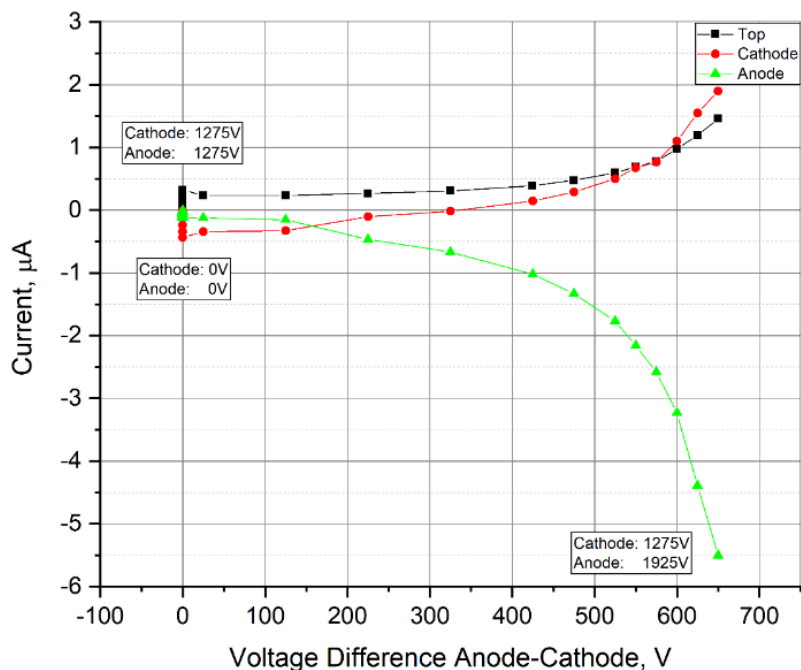


Figure 6. The currents of the THCOBRA electrodes as a function of the voltage difference between anode and cathode strips. The current on the top contact (black squares), the cathode (red circles) and the anode (green triangles) is shown.

images shown in figure 7 were recorded for different applied voltages. The voltage across the holes was kept constant at 1200 V, by biasing the cathode at 1200 V with the top contact grounded. The V_{AC} was increased from 0 V to 650 V. For low absolute values only, the holes provide amplification and therefore light is emitted only from the holes. Increasing V_{AC} leads to the onset of gas gain at the anode strips which begin to contribute to the total gas gain.

And light emitted primarily from the edges and corners of the anode strips indicates a strong electric field at those regions. These observations are in agreement with the interpretation extracted from the measurements of the currents shown above in figure 6.

4.2 Preservation of spatial information during amplification

Measurements in charge-collection mode have previously reported spatial resolution values below 0.5 mm for THCOBRA detectors, which is well below the 1 mm pitch of the holes [15]. In studies carried out with THGEMs [3] a correlation between the source position distribution and the obtained avalanche position distribution was shown. Using a similar method, the THCOBRA was investigated for this preservation of the position information during the avalanche multiplication i.e. a so-called “memory effect”.

The THCOBRA detector was irradiated with a collimated X-ray generator as shown in figure 8. The beam was placed in three different locations: in the middle of a single hole (figure 8a), in the middle of three holes (figure 8b) and in the middle between two holes (figure 8c). As shown in figure 8, there is an asymmetry in the light recorded from holes and anode strips indicating that spatial information might well be preserved in the avalanches. When the beam is centered on a

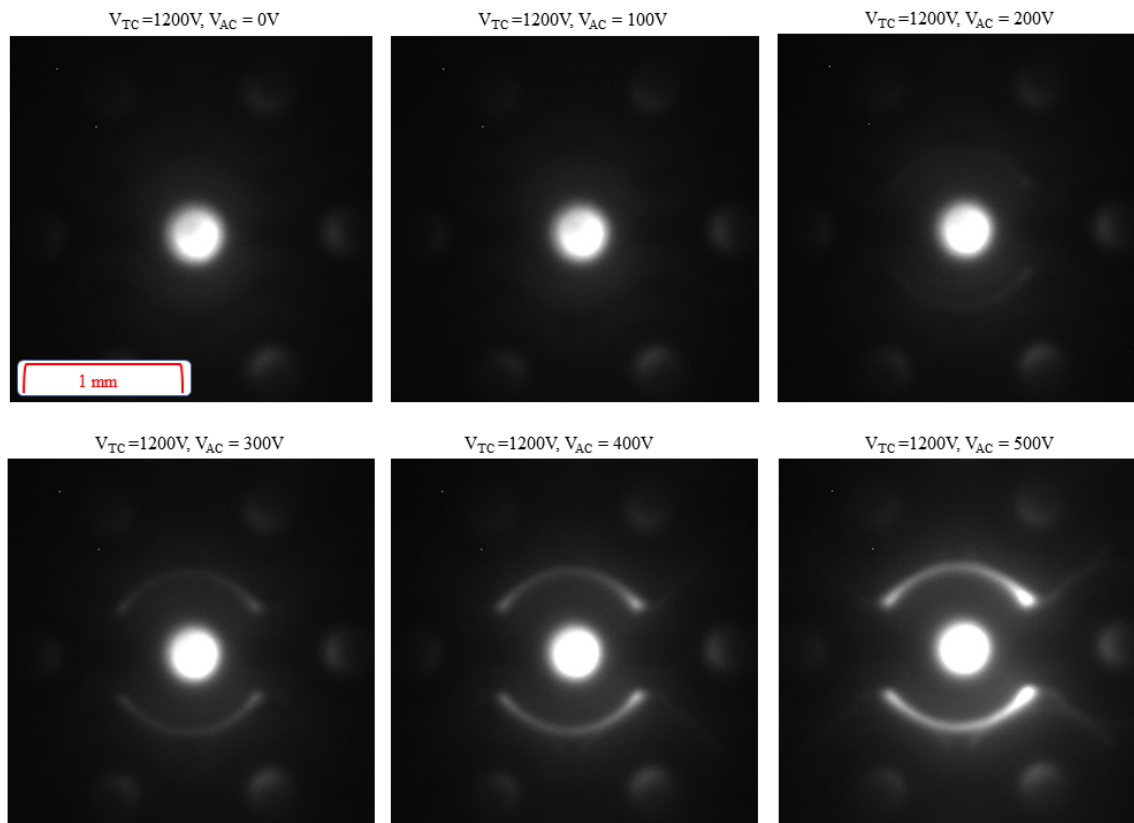


Figure 7. Recorded images of the THCOBRA light emission as a function of the anode-cathode voltage difference. V_{TC} is the voltage across the THGEM hole and V_{AC} is the voltage difference between anode and cathode strips.

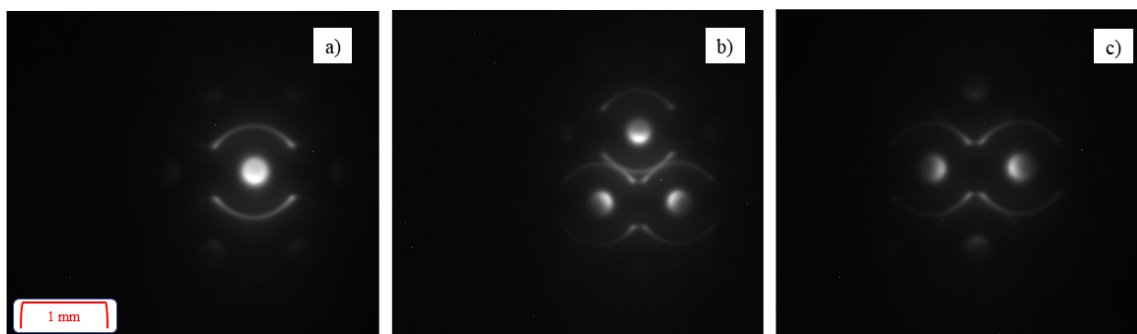


Figure 8. Illumination with a collimated X-rays beam of a single cell of the THCOBRA. The beam is a) centred in the middle of a hole and subsequently is b) centred in the middle of three holes and c) in between two holes.

single hole (figure 8a), only this hole and the anode strips in the vicinity of that hole contribute to the observed charge multiplication and emitted scintillation light. In the recorded image, light is emitted almost uniformly from the hole, with a slight shift towards the bottom which may be attributed to imperfect centering of the X-ray beam with respect to the hole. Both neighboring anode strips are

contributing equally with their corners displaying increased light intensity compared to the central regions of the strips. When the X-ray beam was centred between three holes, all of them were contributing and emitting light (figure 8b). Within each hole, the sides facing towards the incident beam position (center between the three holes) were observed to emit significantly more light than the outer regions of those holes. The same was observed for the anode strips, where only segments of the anode strips in the vicinity of the center between the three holes were contributing strongly to the observed light emission and almost no light was observed from the outward anode strips. The same was observed for the case of the X-ray beam centered in-between two holes (figure 8c), where the amplification and emitted scintillation light was shared between both. The observed light emission for these three cases confirms that spatial information of the incident electrons is retained during the avalanche multiplication. The precise implications of this effect on the achievable spatial resolution of this detector could not be determined with the presented setup, since the two thin GEMs used for pre-amplification above the THCOBRA foil resulted in a widened electron cloud on top of it. Thus, some of the width of the observed light emission profiles might well be a result from the multiplication in the two thin GEMs or from diffusion during the transfer processes. Nevertheless, the observation that only certain regions within the hole or along the anode strips contribute to the observed light emission shows that spatial information of electrons reaching the THCOBRA foil is not completely lost during the avalanche multiplication in this structure.

This was also observed in simulations using Garfield++ [21] in which individual electrons were placed at four different distances from the center and above of the hole (as indicated by the red dots in figure 9). A total of 1000 avalanches were simulated for each starting position. In Fig 9, the black dots represent the end point of each electron of the avalanche on a plane below the hole of the foil. The distribution of the final electron positions after the avalanche displays a dependence on the starting point and thus indicates a preservation of spatial information. While the full hole contributes for the case shown in figure 9a, almost no electrons are observed on the opposite side of the hole, when the arriving electron is outside of it, as shown in figure 9d. This is in agreement with the experimental observations presented above although a quantitative comparison might not be possible due to the widened incoming electron distribution in the experimental study. These findings from simulations match the measurements done in a single THGEM [3] well, where it was experimentally shown that an asymmetries of the avalanche distribution reflect the distribution of the incoming electrons from incident X-rays.

This effect was also observed using photons of 5.9 keV from an ^{55}Fe source and a high-sensitivity EM-CCD camera. The gas gain was increased, using the double GEM stack as pre-amplification stage and images were recorded as shown in figure 10. Recorded images display an asymmetry of the light emitted from these avalanches in the holes and anode strips, which indicates that the initial position of the incoming electrons for a single X-ray event is preserved up to some degree. However, it was not possible to disentangle the charge sharing contribution produced by the two thin GEMs located on top of the THCOBRA and the spread introduced by the THCOBRA foil itself. Further studies are needed to address this effect and quantify each contribution.

4.3 Source of instabilities

While the THCOBRA detector was operating mostly in stable conditions, occasional discharges were observed. In order to understand the origin of these discharges, multiple images of them were recorded and combined together to obtain the single image shown in figure 11.

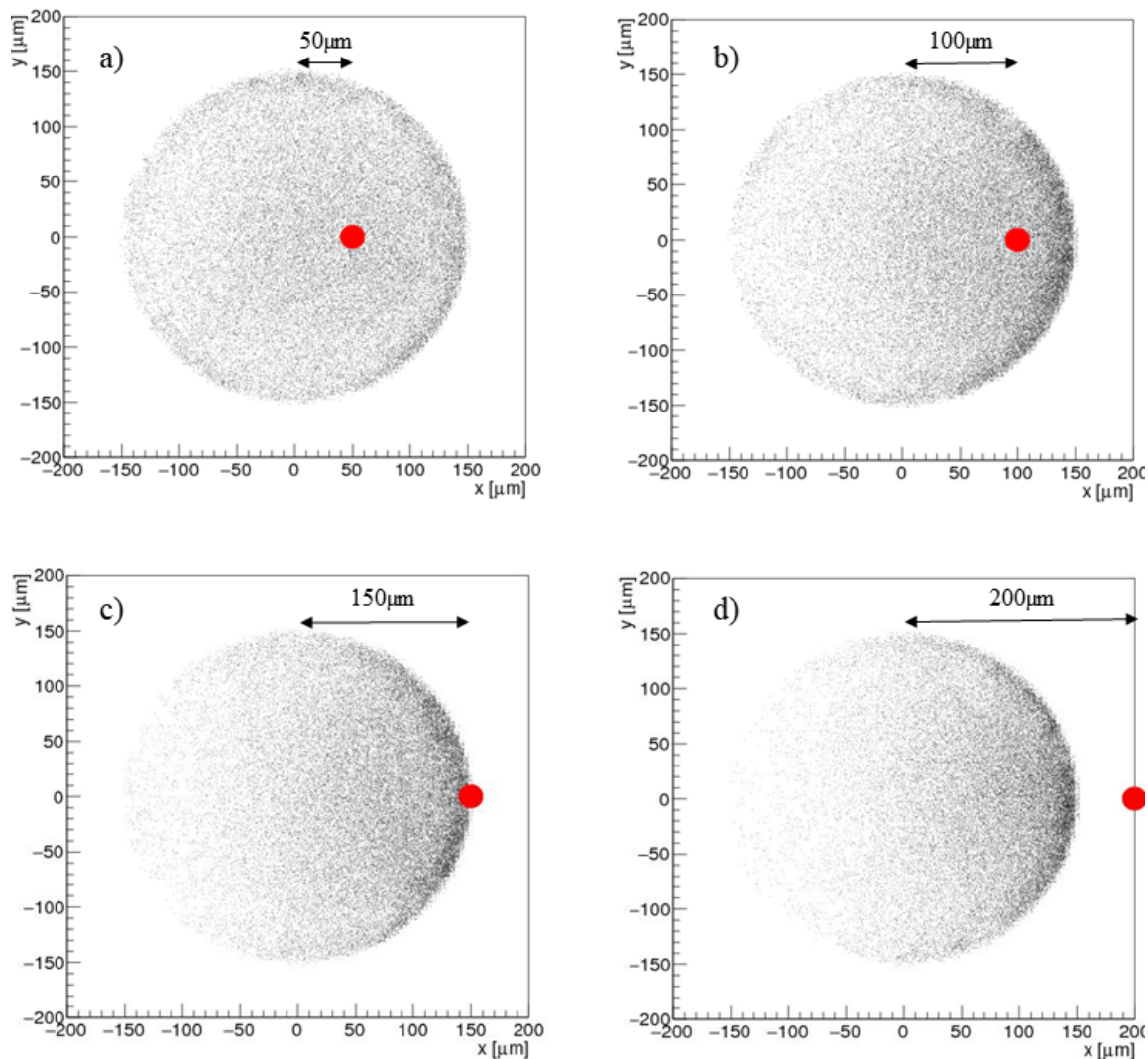


Figure 9. Garfield simulations of the avalanches created by primary electrons. The red point indicates the entry point of the electrons at different distances from the center of the hole: a) $50\ \mu\text{m}$, b) $100\ \mu\text{m}$, c) $150\ \mu\text{m}$ and d) $200\ \mu\text{m}$ from the center of the hole.

Discharges occurred at random locations across the THCOBRA foil, with a preferential orientation towards the narrow regions and corners of the anode strips, indicating the weak point of this electrode structure due to an extremely high increased concentration of electric field lines.

5 Conclusions

In summary, this study allowed a visualization of the THCOBRA operation along with a localization of the sources of instabilities. Followed are some conclusions obtained from this study:

- The optical readout technique was successfully employed to read out a THCOBRA detector.
- The performance of this hybrid structure was visualized. The contributions of the holes were clearly separated from the contribution of the anode strips.

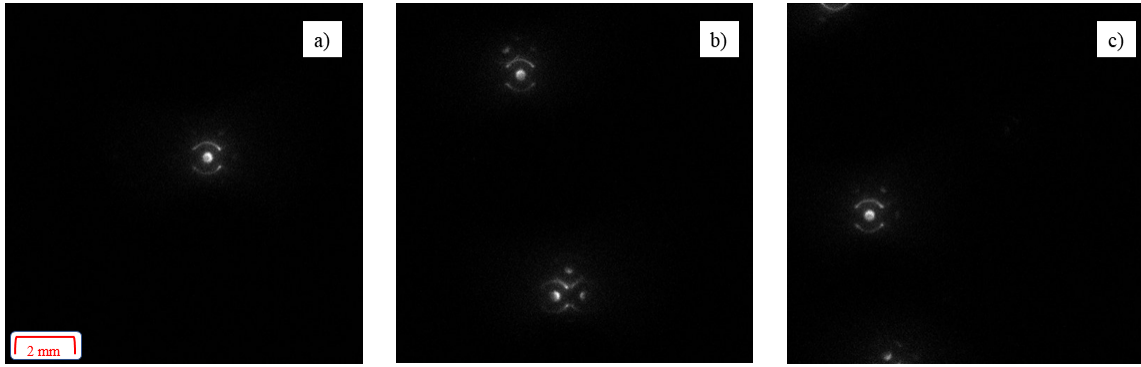


Figure 10. Images of individual low-energy X-ray photon interactions from an ^{55}Fe source.

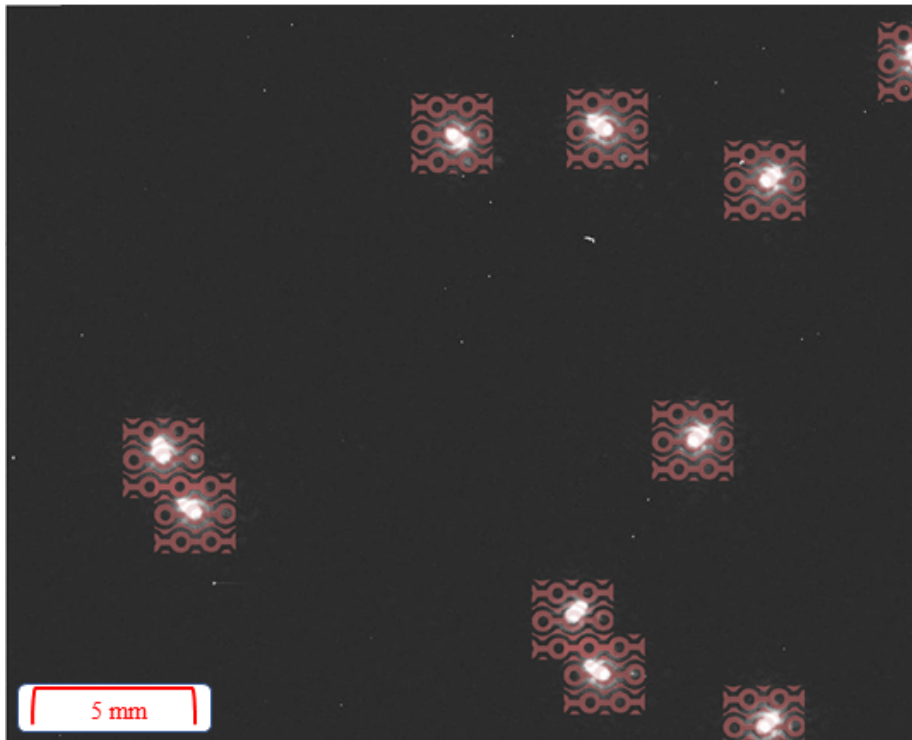


Figure 11. Image of discharges in different locations on the THCOBRA. The layout of the electrodes (red) was overlaid onto the image. Discharges are preferentially oriented towards the narrow regions and corners of the anode strips.

- The so-called “memory effect”, i.e. a preservation of the spatial information from electrons reaching the THCOBRA, was observed. However, it was not possible to disentangle and quantify the contributions from charge sharing and how this affects the spatial resolution of the detector.
- The observation that scintillation light can be emitted from only certain regions within the holes (figure 8) as well as the computed position-dependent avalanche charge distributions (figure 9) show that the spatial position accuracy of THCOBRA structures can be better than the pitch of the holes, as reported in previous studies [3, 15].

The identification of the weak points of this structure, by using the optical readout technique has provided valuable input for the next generation of THCOBRA foils, in terms of how to improve its operation stability.

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