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### **► To cite this version:**

F.M. Brunbauer, D. Desforge, E. Ferrer-Ribas, F.J. Iguaz, B. Mehl, et al.. Radiation imaging with glass Micromegas. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2020, 955, pp.163320. <10.1016/j.nima.2019.163320>. <hal-02458765>

**HAL Id: hal-02458765**

**<https://hal.science/hal-02458765v1>**

Submitted on 21 Jul 2022

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## Radiation imaging with glass Micromegas

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### Abstract

Optically recording scintillation light emitted by MicroPattern Gaseous Detectors (MPGDs) with imaging sensors is a versatile and performant readout modality taking advantage of modern high granularity imaging sensors. To allow scintillation light readout of a detector based on MicroMesh Gaseous Structure (Micromegas) technology, we have integrated a Micromegas on a glass substrate with a transparent anode. In addition to optical detection of scintillation light emitted during electron avalanche multiplication between the micromesh and the anode, this setup also achieves a good energy resolution. A glass Micromegas detector was operated in an Ar/CF<sub>4</sub> gas mixture and showed a response comparable to conventional Micromegas detectors. The spectrum of the emitted scintillation light was recorded and shown to be equivalent to the one obtained with other gaseous detectors in the same gas mixture. Optically read out images were recorded with CCD cameras and integrated X-ray radiographic imaging with good spatial resolution was demonstrated. A spatial resolution of 440  $\mu\text{m}$  (10% MTF) was found. Single X-ray photon detection with a high-sensitivity camera was achieved, which potentially permits energy-resolved X-ray fluorescence imaging.

**Keywords:** radiation imaging, optical readout, MPGD, Micromegas, glass Micromegas, scintillation, ITO

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## 1. Introduction

Optical readout of MicroPattern Gaseous Detectors (MPGDs) takes advantage of combining the high gain factors achievable by MPGD technologies with the high granularity pixel readout permitted by modern imaging sensors. This allows for the realisation of radiation detectors with spatial resolution and sensitivity to a wide range of radiation ranging from Minimum Ionising Particles (MIPs) to low-energy X-rays, as well as highly ionising radiation such as alpha particles. Detector concepts based on optically read out MPGD-based detectors have been previously developed for applications such as radiation imaging [1, 2], 3D track reconstruction in optically read out Time Projection Chambers (TPCs) [3, 4] or dose imaging in hadron therapy [5, 6]. Previous MPGD-based detector concepts employing optical readout with imaging sensors were predominantly based on Gaseous Electron Multipliers (GEMs), a variety of MPGDs consisting of perforated multi-layer foils. This geometry makes GEMs well-suited for optical readout as scintillation light emitted during electron avalanche multiplication can be easily recorded by a camera placed behind the detector. In contrast, most other MPGD technologies are integrated on substrates such as Printed Circuit Boards (PCBs) which are opaque and thus inhibit scintillation light recording. This is also true for MicroMesh Gaseous Structures (Micromegas), which employ a micro-mesh supported by insulating pillars to create a uniform amplification region with an electric field strength sufficient for electron avalanche amplification between the micro-mesh and an anode [7]. However, Micromegas are typically integrated on PCBs, which has previously inhibited the optical readout of such detectors.

We have developed a Micromegas detector on a glass substrate with a transparent anode made of Indium Tin Oxide (ITO) to enable the optical readout of Micromegas-based detectors. Thus it is possible to take advantage of the superior energy resolution reached by this MPGD technology as well as profit from the high spatial resolution and intuitive 2D imaging capabilities associated

30 with optical readout with state-of-the-art imaging sensors.

31 This enables the readout of secondary scintillation light emitted during elec-  
32 tron avalanche multiplication in the amplification gap between the micro-mesh  
33 and the anode. As with the optical readout of GEM-based detectors, the glass  
34 Micromegas were operated in an Ar+CF<sub>4</sub> gas mixture. Gas mixtures con-  
35 taining CF<sub>4</sub> feature wide scintillation light emission bands in the ultraviolet  
36 (UV) and visible (VIS) wavelength ranges [8], which are compatible with the  
37 wavelength-dependent quantum efficiency (QE) of common CCD and CMOS  
38 imaging sensors. Optical readout of GEM-based detectors operated in Ar+CF<sub>4</sub>  
39 gas mixtures has been reported and used for X-ray radiography [1, 2] as well as  
40 3D track reconstruction [3, 4].

41 Optically transparent ITO anodes permitting scintillation light readout have  
42 previously been used to record charge spectra from a glass GEM detector [9] as  
43 well as for track reconstruction in an optically read out TPC [10]. In addition  
44 to featuring high optical transparency, good charge resolution was achieved by  
45 using an ITO layer on a glass substrate as anode.

## 46 2. Experimental setup of the glass Micromegas detector

47 The readout (Fig. 1, left) is a  $6 \times 6 \text{ cm}^2$  bulk Micromegas [11] built on a  
48 1.1 mm thick Borosilicate glass support with an ITO single anode and an ampli-  
49 fication gap of 128  $\mu\text{m}$ , i.e., the distance between the anode and the mesh wires.  
50 The anode, built on the glass support, is a 45 nm thick ITO-layer with a sheet  
51 resistivity of  $15 \Omega/\square$  and an optical transparency of more than 80%. The mesh  
52 is a calendered squared-pattern woven stainless-steel one with 18  $\mu\text{m}$  diameter  
53 wires, a hole aperture of 45  $\mu\text{m}$  and a hole pitch of 63  $\mu\text{m}$ . A microscopic image  
54 of the mesh is shown in Fig. 1 (right). The amplification gap is defined by  
55 500  $\mu\text{m}$  diameter pillars, arranged in square pattern and with a pitch of 6 mm.  
56 The mesh was stressed at a tension of 14 N/cm and laminated onto the glass at  
57 the Micro-Pattern Technologies (MPT) workshop at CERN. Electrical contact  
58 with the mesh and anode was achieved using silver-loaded adhesive.



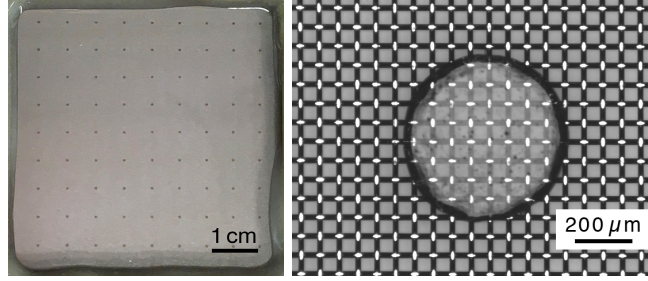


Figure 1: Left: The Micromegas detector prototype, composed of a woven stainless-steel mesh and an ITO coating ( $15 \Omega/\square$ ) for the anode on 1.1 mm thick glass with cylindrical pillars set in a square pattern. Right: Microscopic image of the squared-pattern woven stainless-steel mesh and one pillar.

59 The glass Micromegas was mounted in a gas volume with the glass substrate  
60 acting as a window as shown in Fig. 2. A single GEM mounted 2 mm above  
61 the glass Micromegas could act either as a cathode or as a pre-amplification  
62 stage. The drift volume was defined by a cathode composed of a polyimide foil  
63 coated with Cu, which was mounted 3 mm above the GEM foil. The detector  
64 was operated in an Ar+20%CF<sub>4</sub> gas mixture at atmospheric pressure in open  
65 gas flow mode at 5 l/h.

66 The glass Micromegas detector was optically read out with a low-noise 6  
67 megapixel CCD camera (QImaging Retiga R6) located outside of the gas volume  
68 to demonstrate radiation imaging capabilities. The camera was placed at a  
69 distance of approximately 20 cm from the detector and a 17 mm focal length lens  
70 with an aperture of f/0.95 was used to focus scintillation light emitted in the  
71 detector onto the imaging sensor. The camera featured a  $12.5 \times 10 \text{ mm}^2$  imaging  
72 sensor with  $4.54 \times 4.54 \mu\text{m}^2$  pixels. This setup resulted in a magnification factor  
73 of approximately 10.

74 The detector was operated in a stable condition at voltages of up to 600 V  
75 corresponding to an amplification field of 47 kV/cm. No discharges were ob-  
76 served during several hours of operation.

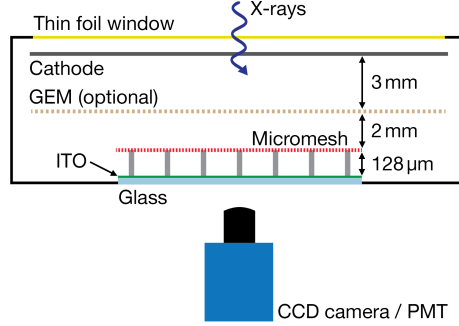


Figure 2: The glass Micromegas detector was mounted in a gas volume with a thin foil radiation window. The glass substrate was used as a window to read out scintillation light with a CCD camera located outside of the gas volume. The drift field was determined with a thin foil cathode and in some tests a GEM was used as pre-amplification structure. Schematic not drawn to scale.

### 3. Detector performance

The energy resolution achievable with optical readout of the prototype detector was measured and compared to the one obtained from the conventional electronic readout of charge signals in the same operational conditions. Energy spectra of an  $^{55}\text{Fe}$  source were acquired by recording electrical signals at the anode of the detector using standard electronics. Simultaneously, scintillation light signals were acquired with a two-inch diameter PhotoMultiplier Tube (PMT, Hamamatsu R375) placed outside of the gas volume in direct contact with the glass substrate of the Micromegas detector. The experimental setup closely resembles the one shown in Fig. 2 with the PMT replacing the camera. The PMT was operated at a voltage of 1000 V yielding a gain of  $2 \times 10^5$ . The radiation source placed in front of the detector was collimated to result in a circular irradiated area with a diameter of approximately 5 mm. Collimation of the source was necessary to record energy spectra of the  $^{55}\text{Fe}$  displaying both the full energy peak as well as the Ar escape peak. When using an uncollimated source, the varying geometric acceptance for detection of scintillation light emitted across the active area resulted in energy spectra, which did not display clearly separated peaks.

95 The energy spectra at a gain of 2000 obtained with electronic and optical  
 96 readout are compared in Fig. 3. An energy resolution of 26 % FWHM was  
 97 achieved when electronically reading out anode signals while a value of 24 %  
 98 FWHM was obtained from scintillation light signals recorded with a PMT. The  
 99 quoted resolution was obtained by fitting the sum of two gaussian functions,  
 100 corresponding to the  $K_\alpha$  (5.89 keV, 24.9 % intensity) and  $K_\beta$  (6.49 keV, 3.4 %  
 101 intensity) emission lines of the  $^{55}\text{Fe}$  source [12], to the energy range close to  
 102 6 keV. The similar energy resolution values for electronic and optical readout  
 103 confirm that optically recorded signals can be used to determine deposited en-  
 104 ergy. This was previously shown for GEM-based detectors and a match between  
 105 electronic and optical energy resolution was also reported [9, 1].

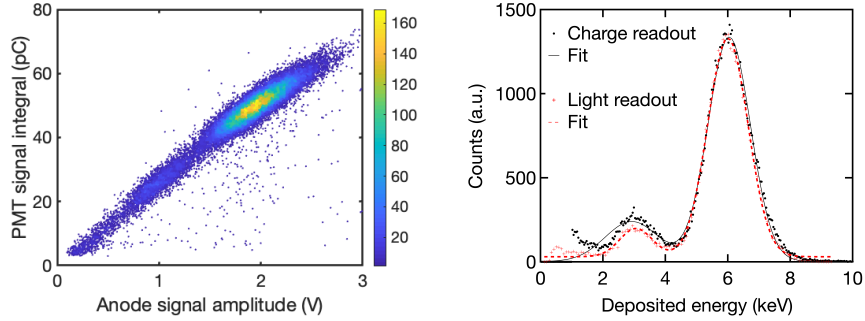


Figure 3: Energy spectra recorded under irradiation with  $^{55}\text{Fe}$  source. Left: Correlation  
 of anode signal amplitudes and PMT signal integrals. Right: An energy resolution of 26 %  
 FWHM was achieved with electronic readout of anode signals and 24 % FWHM was obtained  
 from scintillation light signals.

#### 106 4. Scintillation spectrum and light yield

107 The spectrum of the secondary scintillation light emitted by the glass Mi-  
 108 cromegas detector operated in an Ar+20%CF<sub>4</sub> gas mixture was measured and  
 109 compared to the spectrum of scintillation light emitted by a GEM-based detec-  
 110 tor [8] as shown in Fig. 4.

111 To record scintillation light emission spectra, a 5 mm diameter collimating

112 lens was placed outside of the gas volume directly below the detector in contact  
 113 with the glass substrate on which the Micromegas was integrated. The collected  
 114 light was guided by a 600  $\mu\text{m}$  diameter multi-mode optical fibre to a CCD-based  
 115 UV-VIS spectrometer (Ocean Optics FLAME-S-UV-VIS-ES) capable of record-  
 116 ing spectra in a wavelength range from 200 nm to 800 nm. The spectrometry  
 117 setup was calibrated for absolute irradiance with a deuterium-halogen abso-  
 118 lute irradiance calibration light source. Multiple spectra were acquired with  
 119 an integration time of 10 s each and then averaged. An averaged background  
 120 spectrum recorded with the Micromegas detector switched off was subtracted  
 121 from the acquired light spectra. To achieve sufficient scintillation light intensity  
 122 for recording spectra, the detector was operated under intense X-ray irradiation  
 123 from a Cu X-ray tube operated with an acceleration voltage of 20 kV and a tube  
 124 current of 20 mA. The detector was operated with a drift field of 200 V/cm and  
 125 an amplification field of 43 kV/cm resulting in an anode current slightly below  
 126 2  $\mu\text{A}$ . The acquired spectrum of the scintillation light emission from the glass  
 127 Micromegas detector prototype is shown in Figure 4.

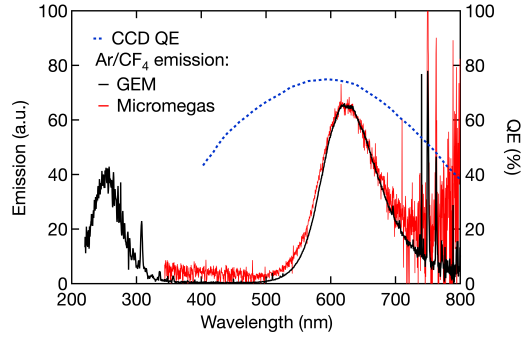


Figure 4: Scintillation light emission spectrum of glass Micromegas detector operated in an Ar+20%CF<sub>4</sub> gas mixture under X-ray irradiation. The QE of the CCD is compatible with the VIS emission band.

128 The recorded scintillation light emission spectrum agrees well with the emis-  
 129 sion spectra previously reported for GEM-based detectors operated in Ar-CF<sub>4</sub>  
 130 gas mixtures [8]. An emission band in the VIS wavelength range centered around

630 nm as well as some sharp emission line in the near-infrared range could be identified. The wide VIS emission band is attributed to emission from  $\text{CF}_4$  molecules, while the sharp emission lines are attributed to photons emitted as a result of transitions between different excited states of Ar atoms. Scintillation light emission in the UV range could not be recorded due to the opacity to UV light of the ITO layer and the glass substrate used as anode. Despite intense irradiation of the detector with an X-ray tube, the total emitted scintillation light intensity was low, which resulted in a significant noise level in the acquired spectra.

The secondary scintillation light yield of the glass Micromegas detector was measured to quantify the intensity of the emitted light. The light yield is defined as the ratio between the number of emitted scintillation photons and secondary electrons produced during electron avalanche multiplication.

Waveforms of PMT signals of individual events were acquired and integrated. The integrated intensity was divided by the integrated intensity corresponding to single photon events detected by the PMT to determine the number of recorded scintillation photons. The single photon response of the PMT was measured with a triggered LED operated at low voltage. Subsequently, the number of photons emitted during electron avalanche multiplication was calculated from the number of photons recorded by the PMT by taking into account correction factors for the geometric acceptance of the PMT and for the detection efficiency. The geometric acceptance correction factors were determined by counting the number of photons originally emitted in random directions from the active area of the detector which end up on the active area of the PMT. The detection efficiency correction factor was determined by multiplying the scintillation spectrum with the transmission of the ITO anode and the glass substrate and the quantum efficiency curve of the employed PMT. The light yield was measured for the configuration of the glass Micromegas detector operated with the GEM used as pre-amplification stage. For a 400 V potential difference across the GEM and an amplification field of 44 kV/cm in the glass Micromegas, a low light yield value of 0.12 ph/e<sup>-</sup> was determined. This value is

significantly lower than previously obtained light yield values of approximately 0.5 ph/e<sup>-</sup> measured for triple-GEM detectors operated in an Ar+10%CF<sub>4</sub> gas mixture [8]. The discrepancy between the light yield values determined for the glass Micromegas detector and GEM-based detectors cannot be explained with the current measurements and is subject to further investigations.

## 5. X-ray radiography

The linearity of the response of the optically read out glass Micromegas detector was investigated by irradiating the detector with X-rays from an X-ray tube at varying beam intensities. The acquired images were obtained by recording the integrated light intensity with the camera in a fixed interval of time. The pixel value intensity in a center region of the acquired images as a function of the X-ray tube current is shown in Figure 5.

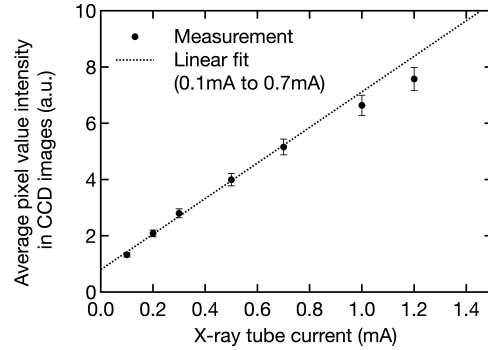


Figure 5: Linearity of CCD response. The averaged pixel value intensity increases almost linearly with the X-ray tube current for low X-ray tube currents and exhibits saturation.

The detector response remained linear at low X-ray fluxes but exhibits saturation at higher X-ray irradiation intensities. Therefore, the recorded pixel value intensity can be used to determine the intensity of the incident radiation at low X-ray fluxes.

The detector response across the active area was investigated by recording uniform exposure images of the detector under irradiation with an X-ray tube.

180 The X-ray tube was positioned approximately 65 cm from the detector to achieve  
 181 an approximately flat irradiation field. A uniform exposure image is shown in  
 182 Figure 6.

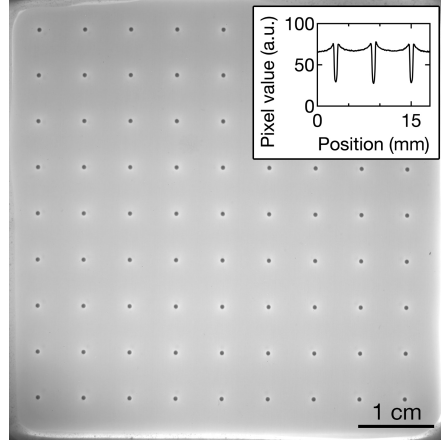


Figure 6: Uniform exposure image of glass Micromegas detector. Inset: Line profile of the pixel value intensity across pillars in the uniform exposure image.

183 The pillars are visible in uniform exposure images and correspond to dead  
 184 regions in the active area of the detector. Around the pillars, increased pixel  
 185 value intensities were observed. This is attributed to an increased number of  
 186 electrons in these regions resulting from the modification of the electric field  
 187 lines in the vicinity of the pillars [13]. However, we cannot exclude an optical  
 188 effect where light is reflected off the pillars and this observation is therefore  
 189 subject to further investigations and may eventually be resolved. A profile of  
 190 the pixel value intensity across pillars in uniform exposure images is shown in  
 191 the inset in Figure 6 and the pillars are clearly visible as dead regions in the  
 192 profile. The brighter regions in the vicinity of the pillars are visible in the line  
 193 profile of the pixel value intensity and appear to extend approximately 2 mm  
 194 away from the pillars.

195 For X-ray radiography, the detector was irradiated with an X-ray tube with  
 196 a Cu target operated at an acceleration voltage of 40 kV and the object un-  
 197 der investigation was placed between the X-ray tube and the detector. A small

198 deceased animal was placed in front of the detector and a transmission X-ray ra-  
 199 diograph was recorded by optically reading out scintillation light from the glass  
 200 Micromegas detector. The detector was operated with an amplification field of  
 201 39 kV/cm corresponding to a gain of approximately  $3 \times 10^2$ . This resulted in  
 202 a total current of 560 nA collected at the anode for an X-ray tube current of  
 203 1 mA. Multiple acquired images were averaged to achieve a high image quality.  
 204 A background image was acquired without any X-ray irradiation and was sub-  
 205 tracted from the acquired radiograph. To correct for the profile of the X-ray  
 206 irradiation field, a “white” image was recorded without any object between the  
 207 X-ray tube and the detector. Subsequently, the radiograph was divided by the  
 208 “white” image to correct for the irradiation field profile. The resulting corrected  
 209 radiograph is shown as the last image in Figure 7.

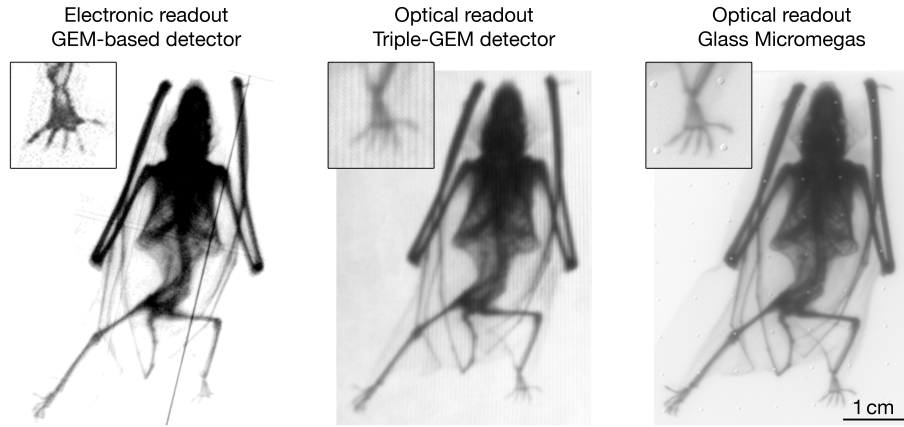


Figure 7: Comparison of transmission X-ray radiographies of a small bat with different detectors and readout modalities. The optical readout of the glass Micromegas detector achieves high resolution and intricate details are visible in the acquired images.

210 High resolution images could be acquired and the X-ray radiograph of the  
 211 small bat shows internal bone structures as well as small features. The use of  
 212 optically read out Micromegas enabled optical readout with higher resolution  
 213 than in the case of triple-GEM-based detectors. This might be partly attributed  
 214 to the localization of the light emission in the holes of GEM-based detectors as



215 shown in the inset in the central image in Figure 7 as well as in Figure 8. The  
 216 glass Micromegas detector, in contrast, is an open system which features contin-  
 217 uous light emission throughout the amplification gap since electron avalanches  
 218 are not confined in the transversal direction. This results in images with a higher  
 219 level of uniformity as shown in the inset in the right image in Figure 7. Im-  
 220 ages acquired with the GEM used as pre-amplification stage were qualitatively  
 221 equivalent to images recorded with the Micromegas only.

222 The achievable spatial resolution in X-ray radiographs acquired by optical  
 223 readout of the glass Micromegas detector was determined by imaging a 50  $\mu\text{m}$   
 224 thick Pb foil with a line pair pattern. The test pattern was placed in direct  
 225 contact with the cathode inside of the gas volume to minimise the distance to  
 226 the active volume of the detector. The Modulation Transfer Function (MTF),  
 227 defined as normalised contrast as a function of line pairs per millimetre (lp/mm),  
 228 was measured and the lp/mm corresponding to a MTF of 10% was used to  
 229 quantify the spatial resolution. For the glass Micromegas detector, a spatial  
 230 resolution of 440  $\mu\text{m}$  could be achieved. For an optically read out triple-GEM  
 231 based detector operated at a higher gain, a spatial resolution of 890  $\mu\text{m}$  was  
 232 determined in a comparable experimental setup. The superior spatial resolution  
 233 of the optically read out glass Micromegas detector may be partly attributed to  
 234 the uniformity of the amplification structure in the case of the Micromegas as  
 235 shown in Figure 8.

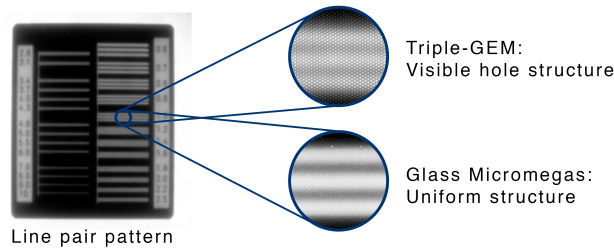


Figure 8: Comparison of optically recorded line pair pattern with GEM-based detector and glass Micromegas.

236 The enhanced energy resolution achievable with Micromegas detectors com-

237 compared to GEM-based detectors makes them an attractive candidate for energy-  
 238 resolved imaging for applications such as X-ray fluorescence. To acquire energy-  
 239 resolved 2D images with an optically read out gaseous radiation detector, short  
 240 exposure images have to be acquired which display individual and distinguish-  
 241 able events. To investigate the applicability of the glass Micromegas detector  
 242 for X-ray fluorescence, short exposure images under irradiation with an  $^{55}\text{Fe}$   
 243 source were recorded. The recording of individual low-energy X-ray photon  
 244 events requires a high detector gain and good sensitivity of the imaging sen-  
 245 sors as the deposited energy of a single event is low. Therefore, the detector  
 246 was operated with a GEM employed as pre-amplification stage with a potential  
 247 difference of 400 V across the GEM. The glass Micromegas was operated with  
 248 an amplification field of 47 kV/cm corresponding to a gain of approximately  
 249  $6.7 \times 10^3$ . In addition, a highly sensitive Electron Multiplying CCD (EMCCD,  
 250 Hamamatsu ImagEM X2 C9100-23B) was used to record secondary scintillation  
 251 light. This camera features a 0.25 megapixel sensor which employs impact ioni-  
 252 sation to amplify signals by factors of up to 1200. This allowed the recording of  
 253 short exposure images of individual low-energy X-ray photon events as shown  
 254 in Figure 9.

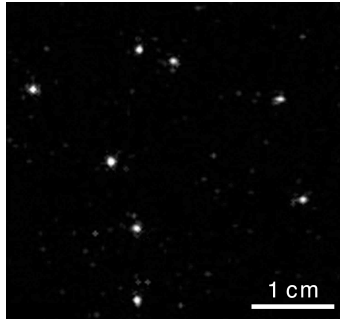


Figure 9: Short exposure image of individual low-energy X-ray photon events from an  $^{55}\text{Fe}$  source acquired by an EMCCD camera.

255 In images recorded with short exposure times, individual X-ray photon  
 256 events can be identified and the integrated pixel value intensities as well as  
 257 the locations can be determined by a centre-of-gravity algorithm. The locations

and integrated intensities of a large number of events can be used for X-ray fluorescence imaging. For this imaging modality, the good energy resolution of the Micromegas detector along with the spatial resolution achieved by optical readout permit full-field energy-resolved imaging.

## 6. Conclusions

A Micromegas detector was integrated on a glass substrate with a transparent ITO layer as anode. Operating in an Ar+20%CF<sub>4</sub> gas mixture, secondary scintillation light emitted during electron multiplication in the amplification zone was recorded. The light emission spectrum was shown to be equivalent to the one of GEM-based detectors. A lower light yield normalised to the electronic gain compared to GEM-based detectors was measured.

The detector achieved a spatial resolution of 440  $\mu\text{m}$  corresponding to a MTF of 10%. The superior spatial resolution compared to triple-GEM-based detectors is attributed to the uniformity of the amplification region and makes the glass Micromegas detector well-suited for imaging. Additionally, it achieves sufficient gain for recording individual low-energy X-ray photon events permitting energy-resolved imaging. Incorporating the glass Micromegas detector with ultra-fast imaging sensors and on-camera image processing, effective full-field X-ray fluorescence imaging might be realised. Recording and processing images at rates of several kHz and extracting tens of events from each frame may be used to rapidly assembly energy-resolved images.

The demonstrated possibility to integrate a Micromegas detector on a glass substrate enables the combination of this MPGD technology with optical readout. Thus, it can be used to benefit from the good energy resolution of Micromegas and the high granularity of imaging sensors.

## Acknowledgements

We acknowledge the support of C. Bault (CERN) in constructing the experimental setup used for optical readout of the Micromegas detector. F.J. Iguaz ac-

286 knowledges the support from the Enhanced Eurotalents program (PCOFUND-  
287 GA-2013-600382).

## 288 References

- 289 [1] F. M. Brunbauer, M. Lupberger, E. Oliveri, F. Resnati, L. Ropelewski,  
290 C. Streli, P. Thuiner, M. Van Stenis, Radiation imaging with optically  
291 read out GEM-based detectors, JINST 13 (02) (2018) T02006. [doi:10.1088/1748-0221/13/02/T02006](https://doi.org/10.1088/1748-0221/13/02/T02006).  
292
- 293 [2] T. Fujiwara, Y. Mitsuya, T. Fushie, K. Murata, A. Kawamura,  
294 A. Koishikawa, H. Toyokawa, H. Takahashi, [Gas scintillation glass](#)  
295 [GEM detector for high-resolution X-ray imaging and CT](#), Nucl. In-  
296 struments Methods Phys. Res. Sect. A 850 (January) (2017) 7–11.  
297 [doi:10.1016/j.nima.2017.01.013](https://doi.org/10.1016/j.nima.2017.01.013).  
298 URL [http://dx.doi.org/10.1016/j.nima.2017.01.013http:](http://dx.doi.org/10.1016/j.nima.2017.01.013http://linkinghub.elsevier.com/retrieve/pii/S016890021730013X)  
299 [//linkinghub.elsevier.com/retrieve/pii/S016890021730013X](http://linkinghub.elsevier.com/retrieve/pii/S016890021730013X)
- 300 [3] L. Margato, F. Fraga, S. Fetal, M. Fraga, E. Balau, A. Blanco, R. F. Mar-  
301 ques, A. Policarpo, Performance of an optical readout GEM-based TPC,  
302 Nucl. Instruments Methods Phys. Res. Sect. A 535 (1-2) (2004) 231–235.  
303 [doi:10.1016/j.nima.2004.07.126](https://doi.org/10.1016/j.nima.2004.07.126).
- 304 [4] F. M. Brunbauer, G. Galgoczy, D. Gonzalez Diaz, E. Oliveri, F. Resnati,  
305 L. Ropelewski, C. Streli, P. Thuiner, M. van Stenis, Live event reconstruc-  
306 tion in an optically read out GEM-based TPC, Nucl. Instrum. Meth. A886  
307 (2018) 24–29. [doi:10.1016/j.nima.2017.12.077](https://doi.org/10.1016/j.nima.2017.12.077).
- 308 [5] E. Seravalli, M. de Boer, F. Geurink, J. Huizenga, R. Kreuger, J. M. Schip-  
309 pers, C. W. E. van Eijk, B. Voss, A scintillating gas detector for 2D dose  
310 measurements in clinical carbon beams, Phys. Med. Biol. 53 (17) (2008)  
311 4651–4665. [doi:10.1088/0031-9155/53/17/013](https://doi.org/10.1088/0031-9155/53/17/013).

- [6] A. Klyachko, V. Moskvina, D. Nichiporov, K. Solberg, A GEM-based dose imaging detector with optical readout for proton radiotherapy, Nucl. Instruments Methods Phys. Res. Sect. A 694 (2012) 271–279. [doi:10.1016/j.nima.2012.08.049](https://doi.org/10.1016/j.nima.2012.08.049).
- [7] Y. Giomataris, P. Rebourgeard, J. P. Robert, G. Charpak, MICROMEGAS: A High granularity position sensitive gaseous detector for high particle flux environments, Nucl. Instrum. Meth. A376 (1996) 29–35. [doi:10.1016/0168-9002\(96\)00175-1](https://doi.org/10.1016/0168-9002(96)00175-1).
- [8] M. M. F. R. Fraga, F. A. F. Fraga, S. T. G. Fetal, L. M. S. Margato, R. Ferreira-Marques, A. J. P. L. Policarpo, The GEM scintillation in He CF-4, Ar CF-4, Ar TEA and Xe TEA mixtures, Nucl. Instrum. Meth. A504 (2003) 88–92. [doi:10.1016/S0168-9002\(03\)00758-7](https://doi.org/10.1016/S0168-9002(03)00758-7).
- [9] T. Fujiwara, Y. Mitsuya, T. Yanagida, T. Saito, H. Toyokawa, H. Takahashi, [High-photon-yield scintillation detector with Ar/CF 4 and glass gas electron multiplier](https://doi.org/10.7567/JJAP.55.106401), Jpn. J. Appl. Phys. 55 (10) (2016) 106401. [doi:10.7567/JJAP.55.106401](https://doi.org/10.7567/JJAP.55.106401).  
URL <http://stacks.iop.org/1347-4065/55/i=10/a=106401?key=crossref.06ddd4ef4ef46b01583560ee0b4075f9>
- [10] F. M. Brunbauer, F. Garcia, T. Korkalainen, A. Lugstein, M. Lupberger, E. Oliveri, D. Pfeiffer, L. Ropelewski, P. Thuiner, M. Schinnerl, Combined optical and electronic readout for event reconstruction in a GEM-based TPC, IEEE Trans. Nucl. Sci. 65 (3) (2018) 913–918. [doi:10.1109/TNS.2018.2800775](https://doi.org/10.1109/TNS.2018.2800775).
- [11] I. Giomataris, et al., Micromegas in a bulk, Nucl. Instrum. Meth. A560 (2006) 405–408. [doi:10.1016/j.nima.2005.12.222](https://doi.org/10.1016/j.nima.2005.12.222).
- [12] U. Schötzig, H. Schrader, Halbwertszeiten und photonen-emissionswahrscheinlichkeiten von häufig verwendeten radionukliden, Tech. Rep. PTB-Ra-16/5, Physikalisch-Technische Bundesanstalt (1998).

- 340 [13] O. Sidiropoulou, [Characterization of the ATLAS-type Micromegas Detec-](#)  
341 [tors](#), Ph.D. thesis, Julius-Maximilians-Universität Würzburg (2018).  
342 URL [https://opus.bibliothek.uni-wuerzburg.de/frontdoor/index/](https://opus.bibliothek.uni-wuerzburg.de/frontdoor/index/index/docId/16732)  
343 [index/docId/16732](https://opus.bibliothek.uni-wuerzburg.de/frontdoor/index/index/docId/16732)