X-ray imaging detector based on a position sensitive THCOBRA with resistive line

A.L.M. Silva,\textsuperscript{a,1} C.D.R. Azevedo,\textsuperscript{a} L.F.N.D. Carramate,\textsuperscript{a} T. Lopes,\textsuperscript{a} I.F. Castro,\textsuperscript{a} R. de Oliveira\textsuperscript{b} and J.F.C.A. Veloso\textsuperscript{a}

\textsuperscript{a}I3N — Physics Department, University of Aveiro, 3810-193 Aveiro, Portugal
\textsuperscript{b}TS Division, CERN, CH-1211 Geneva 23, Switzerland

E-mail: analuisa.silva@ua.pt

ABSTRACT: A new X-ray imaging detector based on a 2D-THCOBRA micropatterned structure using a simple position readout is proposed. It consists of a hybrid device that combines the properties of a THGEM and a 2D-MHSP in a single structure, having two charge multiplication stages reaching the demanded gains for the use of charge division readout methods.

For position determination, the new $10 \times 10 \text{cm}^2$ 2D-THCOBRA structure uses two orthogonal resistive lines located at the end of the anode and top electrodes. The charge signal pulses collected at the end of each resistive line are digitized and processed in order to determine the center-of-gravity of the electron avalanche distribution.

The detector uses a preamplification stage performed by a THGEM, followed by the 2D-THCOBRA, being operated in Ne/5\% CH\textsubscript{4} at atmospheric pressure. A characterization of the detector in terms of charge gain was made as a function of the voltage applied to the electrodes of the 2D-THCOBRA structure. The energy resolution of the system was also measured, envisaging Energy Weighting Technique (EWT) applications.

The system characterization in terms of spatial resolution is presented together with imaging examples to evaluate its performance in X-ray imaging applications.

KEYWORDS: Gaseous detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); X-ray fluorescence (XRF) systems; X-ray detectors

\textsuperscript{1}Corresponding author.
1 Introduction

Following the success of the 2D-Micro-Hole and Strip Plate (2D-MHSP) obtained for single photon X-ray detection and imaging [1], a new detector based on a similar concept is presented. The Thick-COBRA (THCOBRA) structure [2] was developed with 2D capability for X-ray imaging (2D-THCOBRA) (figure 1).

The THCOBRA structures [2] have been recently introduced and are very promising devices in the field of gaseous detectors, due to their robustness inherited from Thick Gas Electron Multiplier (THGEM) [3]. These patterned structures are produced by mechanical drilling and etched using standard printed circuit board (PCB) technology [2].

The advantage of using a single photon counting device for X-ray imaging is mainly related with the possibility of storing, not only the interaction position of each detected photon, but also its energy. This allows improving the image contrast, according to the density of the imaged object. Furthermore, the energy information can be also used for contrast enhancement by using techniques such as the Energy Weighting Technique (EWT) [4, 5], in which the intensity of each pixel is obtained by weighting each event by a factor that depends on its energy \(1/E^3\), leading to the maximization of the image signal-to-noise ratio for energies up to 40 keV [4]. Also, these features are quite adequate to another very interesting application as it has been discussed in recent work developed with MPGDs: Energy Dispersive X-ray Fluorescence imaging [6, 7].

A characterization of the new X-ray imaging detector, using photons provided by an X-ray tube and the fluorescence K-lines of single-element targets, is presented.

2 Operation principle and acquisition setup — 2D-THCOBRA

The detector system is composed by an aluminum vessel containing a metallic mesh in order to define the converter/drift region, a THGEM and a THCOBRA disposed in a cascade configuration.
The 10 × 10 cm$^2$ THGEM (0.4 mm thickness, 0.3 mm hole diameter, 0.1 mm rim and 1 mm pitch) performs a preamplification stage to increase the total gain charge of the detector, as shown in figure 2.

The 2D-THCOBRA has an active area of 10 × 10 cm$^2$. It is a double-sided structure made out of a 0.4 mm thick G10 plate, covered with 50 µm of copper on both sides. The THCOBRA has a 0.3 mm hole diameter, a pitch of 1 mm and a rim of 0.08 mm.

On the bottom side a pattern of strips is etched: a circular electrode surrounding each hole with 0.2 mm wide (cathode) and about 0.2 mm wide anode strip, as shown in figure 1. For the second dimension, the top copper side is also structured in several different strips perpendicular to the anode strips. Two resistive lines of about 50 Ω/mm, one for each dimension, are orthogonally disposed, connecting respectively the anode strips and the top strips of the 2D-THCOBRA, similarly to the 2D-MHSP [1] (see figure 1).

The operation principle of the 2D-THCOBRA detector is illustrated in figure 2. The gas used (Ne/5%CH$_4$) acts as the absorption and multiplication medium. The electrons produced in the
conversion/drift region are focused into the holes of the THGEM and multiplied. The resulting charge drifts through the transfer region until it reaches the 2D-THCOBRA holes, where the first 2D-THCOBRA charge multiplication stage occurs due to the intense electric field in the holes, produced by the voltage difference between the cathode and the top strips \( V_{CT} \), typically 440 V. By controlling the voltage difference between the circular-cathode strips and the anodes \( V_{AC} \), typically 150 V, a second multiplication can occur. The charge is collected at the anode strips [1, 2, 7].

For 2D imaging, two orthogonal resistive lines are used for position readout, one connecting the anode strips and the other connecting the top strips of the structure, as shown in figure 3. The charge collected on the anode and the induced charge on the top strips are read from both ends of each resistive line and the interaction position is determined according to the principle of resistive charge division [1]. This simple readout system composed by resistive lines is very cost effective since it requires only 4 electronic channels to process the signals and therefore obtain an image [1].

The charge signals from the 2D-THCOBRA were integrated by four Canberra 2006 preamplifiers, each connected to one end of the resistive lines. For signal processing, a NIM module N1728 from CAEN was used, with a 4-channel, 14 bit, 100 MHz ADC card. The signals were digitally shaped and amplified by applying the Jordanov trapezoid algorithm to determine the signal amplitudes. For more details on the readout electronics please see reference [1].

3 2D imaging system characterization

3.1 Charge gain

To evaluate the charge multiplication properties of the new 2D-THCOBRA detector, a study of the charge gain as a function of the \( V_{AC} \) and \( V_{CT} \) was performed.

The results were obtained using X-rays from Cu K lines, which produce the primary charge in the drift region of the detector.

The final charge produced by each event was collected at the anodes and at the tops of the THCOBRA by using a Canberra 2006 preamplifier (connected to one end of the resistive line) fed
Figure 4. Charge calibration setup scheme.

to a Canberra 2022 Spectroscopy Amplifier (shaping time of 0.5 µs). The output of the amplifier was connected to an Amptek MCA8000A multichannel analyser.

The front-end electronics was calibrated by the injection of a known charge (using a calibrated 6.8 pF capacitor with a 3.8% tolerance and a BNC PB-5 Precision Pulse Generator) into the preamplifier input. The electronic chain setup used for calibration is illustrated in figure 4. In this way it is possible to measure the charge corresponding to each ADC channel, which allows determining the collected charge for a given deposited energy.

In order to estimate the final charge produced by the 8 keV photons (Cu K-lines), a Gaussian function was fitted to the total absorption peak of the pulse-height distribution and the centroid position was determined.

The gain is then given by the coefficient of the final charge over the average of the number of primary electrons (269.3 electrons) produced by the 8 keV in Ne/5%CH4. The $W_{value}$ for the Ne mixture used, was calculated by using the gas simulation program Magboltz/Mip [8] and was found to be 29.7 eV/ion-pair. The charge gains obtained as a function of $V_{AC}$ and $V_{CT}$ applied to the 2D-THCOBRA electrodes, for anode and top signals, are presented in figure 5 a) and b).

The results show, as expected, that the charge gain increases exponentially with the increase of both $V_{AC}$ and $V_{CT}$. It can also be seen that the charge gain increase is faster with the increase of $V_{CT}$ than with that of $V_{AC}$, reflecting the large width of the anode strips for efficient charge multiplication.

As mentioned, for position resolution performance, it is important to evaluate the gain related to the charge collected in the anode strips, but also to the charge induced in the top strips. As it can be seen from figure 5, the anode signal amplitudes always reveal slightly greater gains in both cases ($V_{AC}$ and $V_{CT}$ variation), when compared to the top signal amplitudes. This is due to the fact that the charge signals collected from the top side (top strips) are induced by the charge produced on the bottom side (anode strips), which makes them typically 60% [1] of the anode signals, due to the 2D-THCOBRA substrate thickness.

Nevertheless, in figure 5 it is visible that as the $V_{CT}$ increases, the gain in charge of the anodes and the tops tends to approach. With the increase of the electric field in the holes, part of the
ions created in the avalanche is further collected on the tops, increasing the collected charge and therefore increasing the charge gain.

The maximum gain, before discharges, obtained by the detector operating in Ne/5%CH$_4$ was about $2.5 \times 10^4$, for a $V_{CT}$ of 430 V and a $V_{AC}$ of 190 V. The detector shows very good stability, even at count rates as high as 100 kHz (per channel). The low slope of the gain as a function of $V_{AC}$ indicates that thinner anode strips need to be considered in order to reach higher gains.

3.2 Energy resolution

The energy resolution of the system was measured envisaging EWT applications [5, 6].

The energy resolution was determined using the fluorescence X-ray lines obtained from different single-element targets of Ti, Fe, Ni and Cu.

The single-element targets, placed 20 cm away from the detector window, were excited through irradiation of an X-ray tube. In order to irradiate just a small area of the detector a lead collimator
with a 4 mm diameter hole was coupled to the detector window. Therefore, by summing the charge collected from both ends of the resistive line, a pulse height distribution of the characteristic X-ray of the target element was acquired. The obtained spectra can be seen in figure 6 a).

The energy resolution was determined by fitting a Gaussian distribution to the peak of the fluorescence K lines, and was found to be 23.8%, 21.4%, 20.4% and 20.3%, for Ti, Fe, Ni and Cu respectively, as shown in figure 6 b).

3.3 Spatial resolution

To determine the position resolution of the imaging system, a lead slit of 1 mm was illuminated, in two orthogonal directions by an X-ray tube (Oxford®, series 5000 Apogee) operating at 20 kV and 300 µA. Figure 7 a) and figure 7 b) correspond to the anodes strips direction and top strips electrodes direction, respectively. Since the spatial resolution is directly related with the signal-to-
Figure 7. a) Line spread function (LSF) obtained with a 1 mm slit in the horizontal position. b) LSF obtained with the slit in the vertical position.

noise ratio (SNR) it is expected that slightly better results will be achieved for the anodes direction compared to the top strips one.

A small area of the image, marked with a red rectangle was selected to calculate the line spread function (LSF) [7] of the slit, shown in figure 7 a) and figure 7 b).

A Gaussian function was fitted to the LSF distribution and the Full Width at Half Maximum (FWHM) was determined. Considering the LSF as a pure Gaussian distribution, the FWHM was found to be 2.34 mm for the anodes direction (figure 7 a)) and 2.78 mm for the top strips direction (figure 7 b)).

The achieved spatial resolution needed to be corrected due to the finite size of the considered rectangle width [9], and was then found to be about 2.29 mm for the anodes direction (figure 7 a)) and 2.73 mm for the top strips direction (figure 7 b)).
Nevertheless, this position resolution is strongly limited by the gas medium used, which is based on Ne mixtures, not reflecting the intrinsic capabilities of the 2D-THCOBRA structure for position resolution.

The Continuous Slowing Down Approximation (CSDA) [10] range is a measure of the mean path length of the particle’s trajectory in the absorbing medium. In figure 8, the CSDA range of electrons in Ne is presented, which is a good approximation for the photoelectron range in Ne/5\%CH\textsubscript{4} since the gas mixture is mostly composed by Ne. As it can be seen, the photoelectron range in Ne is quite large (e.g. about 3 mm for 10 keV) and for that it becomes the main limiting factor of the spatial resolution. It is important for the present application to consider higher Z gases.

However, position resolution below 0.5 mm was already obtained for a position sensitive gaseous photomultiplier with a CsI photocathode and a 2D-THCOBRA electrode readout [11].

### 3.4 2D imaging applications

In order to test the performance of the system for X-ray imaging, different objects were imaged: a stainless steel mask, a slice of human tooth sample and a tree leaf. To perform these experiments, the detector, filled with Ne/5\%CH\textsubscript{4} was operating with a \( V_{AC} \) of 150 V and a \( V_{CT} \) of 440 V, and with a \( V_{THGEM} \) of about 700 V. No EWT technique was used. The exposure time was of about 20 min.

The stainless steel mask (0.5 mm thickness) with the University of Aveiro logo was placed between the X-ray tube with a Mo anode and a maximum power of 50 W and the detector. The object was projected on the detector window, producing the image shown in figure 9.

The image is well defined despite some smaller image artifacts.

By using the same procedure two biological samples, a tree leaf and a restored tooth sample, were imaged. The resulting images are shown in figure 10 and figure 11.

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1. ESTAR: Stopping Powers and Ranges for Electrons http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html.
Figure 9. Stainless steel mask with the symbol of the University of Aveiro and the X-ray transmission image. X-ray tube operation conditions: 20 kV; 320 µA.

Figure 10. Photo of the leaf tree and the correspondent X-ray image. X-ray tube operation conditions: 5.8 kV; 630 µA.

In figure 10 it is possible to clearly see the outline of the leaf and its main ribs, although there are some artifacts visible in the image around two most intense lines which are possibly due to an effect of the electronic reading process.

The first results obtained with a human tooth (figure 11) have demonstrated a reasonable image definition, allowing to distinguish the pulp and the root channel of the tooth, which shows that the 2D-THCOBRA detector is a promising device for X-ray transmission imaging.

4 Conclusions

The 2D sensitive THCOBRA with resistive line readout system indicates good prospects for X-ray imaging purposes. The results obtained have shown a fair energy resolution capability of about
Figure 11. Photo of the human tooth imaged. X-ray transmission image of the tooth. X-ray tube operation conditions: 16 kV; 20 µA.

22% (FWHM) for 5.9 keV, and a charge gain above $10^4$ in Ne/5%CH₄. Although the position resolution was limited to about 2.5 mm due to the high photoelectron range in the present mixture (Ne/5%CH₄), a recent study using a CsI photocathode and a 2D-THCOBRA structure, has achieved a spatial resolution below 0.5 mm for single photoelectron [11].

For future work, an improvement of the position resolution and detection efficiency will be done by using higher Z gases (e.g. Ar, Kr and Xe), as well as reducing the anode strips width in order to reach higher gains for lower applied voltages.

Methods for image enhancement will also be implemented, such as image artifacts correction and EWT.

Acknowledgments

This work was partially supported by project CERN/FP/123604/2011 and PTDC/FIS/113005/2009 through COMPETE, FEDER and FCT (Lisbon) programs. A.L.M. Silva, L.F.N.D. Carramate and I.F. Castro are supported by a doctoral grant from FCT (Lisbon) with the respective references SFRH/BD/61862/2009, SFRH/BD/71429/2010 and SFRH/BD/61255/2009. C.D.R. Azevedo is supported by a Postdoctoral grant from FCT (Lisbon) with the reference SFRH/BPD/79163/2011. Part of the research work was done within the CERN RD51 collaboration.

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