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# Soft X-ray measurements with a gas detector coupled to microchips in laser-plasma experiments at VEGA-2

**G .Claps,[a,b] F. Cordella,[a,b] D. Pacella,[a,b,1] A. Romano,[a] F. Murtas,[b] D. Batani,[c] O. Turianska,[c] D. Raffestin,[c] L. Volpe,[d,e] G. Zerauili,[d,e] J.A. Perez-Hernandez,[d] and S. Malko[d,e]**

[a] *ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Frascati, Italy*
[b] *INFN — Laboratori Nazionali di Frascati, Via Enrico Fermi 40, 00044 Frascati, Italy*
[c] *CELIA Université Bordeaux, 49 rue Pierre Noailles, 33405 Talence, France*
[d] *CLPU, Centro de Laseres Pulsados, Scientific Park, Building M5, C/Adaja 8, 37185 Villamayor — Salamanca, Spain*
[e] *CLPU Laser-Plasma Chair at University of Salamanca, Salamanca Spain*

*E-mail:* danilo.pacella@enea.it

Abstract: This work presents an innovative usage of the GEMpix detector for soft X-rays (SXR) measurements aimed to make an estimate of the electron temperature of a Laser Produced Plasma (LPP). The GEMpix is a proportional gas detector based on three Gas Electron Multipliers (GEMs) with a Front-End Electronics (FEE) based on four Timepix chips. This FEE provides the Time over Threshold (ToT) acquisition mode pixel by pixel and then a digital measure of the released charge in the gas mixture. In addition, the charge can be amplified through the GEM foils with 4 orders of magnitude spanning gain offering, in this way, a big dynamic range and adjustable sensitivity. Chip design provides a threshold for each channel. All the thresholds are set in order to cut electronic noise and detect X-rays. In this configuration, a cut on the low amplitude signals is set, but the gain has been tuned in order to observe the main signal due to the soft X-rays reaching the detector. This detector works in an energy range between 2 to 15 keV. It offers good imaging properties, high efficiency and absolute calibration. It offers a good immunity to Electromagnetic Pulse (EMP), as

[1] Corresponding author.


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checked at VEGA-2 laser facility (hundreds of TW in about 30 fs). In these experiments, where the formation of warm dense matter produced by blast waves has been studied, a measure of the plasma temperature was required. This measurement was realized applying some filters on the active area of the detector, in correspondence of three chips. With this configuration a study of the GEMpix response due to the photons coming from the coronal plasma produced by the laser on the target has been done for each single shot. GEMpix revealed innovative and attractive features, compared to the state of the art where passive films or detectors based on indirect conversion are used, for SXR imaging and spectral analysis to infer the electron temperature.

Keywords: CMOS readout of gaseous detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Nuclear instruments and methods for hot plasma diagnostics; X-ray detectors

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## Contents



# 1 GEMpix detector as soft-X rays monitor

## 1.1 Introduction

GEMpix detector, in figure 1, is a gas-proportional-based detector build with a cathode, an anode and three consecutive GEM foils [1] in the middle. The detector window is made of a 12 µm Mylar foil with a side covered with a 100 nm aluminium layer which works as detector cathode. The anode consists of four Timepix chips, with $512 \times 512$ squared pixels, each 55 µm wide [2].

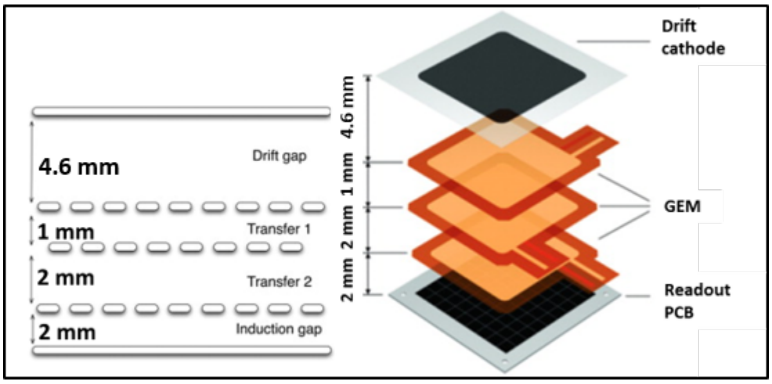


**Figure 1**. A schematic layout of the GEMpix detector [5]. Four regions are defined: drift gap (the active gas layer), transfer1 and transfer2 regions and the induction gap.

The gas layer ("drift region") in the gap between the cathode and the first GEM foil has a thickness of 4.6 mm and represents the active volume of the detector. After the active region, the other gaps have a thickness of 1, 2, 2 mm, respectively and by now are the standard in other GEMpix detector applications [3, 4]. In order to transport and to amplify the charge released in the active volume, the GEMs and gaps (figure 1) are biased with increasing negative voltages, while the anode is grounded. Changing the voltages applied to the GEM foils, the primary charge converted in



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the drift region can be amplified passing through the foils, up to thousands of times. Therefore GEMpix, thanks to this intrinsic adjustable gain, can measure a charge released by photon fluences up to six orders of magnitude of the charge. Indeed, for laser-plasma, where X-rays are produced into sub-nanosecond scales, the measurement in counting mode is not possible and a pile-up mode acquisition is used measuring the total released charge. For this purpose, Time-over-Threshold (ToT) acquisition mode is set on the readout electronics. ToT is based on the Wilkinson ADC: the induced current peak charges a pre-amplifier, the output signal is measured if it is over the set threshold level, then it switches off with a time constant and a discriminator provides a constant output signal until the threshold level is reached. The time duration of the discriminator output signal is measured by an internal clock which provides the digital ToT counts [2]. Then, for GEMpix detector, a pixel working in ToT mode provides a digital measure of the total charge released in the gas mixture by all the detected photons (integrated charge). Pixels matrix provides also a 2-D charge spatial reconstruction released by a given photon fluence. In the present case, the energy fluence can be considered uniformly distributed because the plasma source is placed at a distance of 50 cm and observes the source under a solid angle lower than 3 msr. As a consequence, a uniform measure of the released charge corresponds to a uniform photon fluence. For each pixel there is a threshold and, in the present case, a threshold level has been set in order to cut all the electronic noises and external electromagnetic disturbances. However, it was observed that the contribution coming from external disturbances was negligible.

### 1.2 Laboratory calibration

In order to fully exploit the charge response of this detector and its intrinsic gain, detailed tests and calibrations have been performed in laboratory, the detector response to the single photon was characterized. The interaction of the single photon produces signals on the pixels with a blob-like pattern. Its diameter depends on gas mixture, photon energy, and gain voltage. These tests have been published in previous work [5]. This behavior has been studied for the $ArCO_2$ gas mixture which is our standard for the measurements on the Laser Produced Plasmas (LPPs). In the experiment presented in [5], a laser having the wavelength of 800 nm, the power per pulse of 170 mJ and the pulse time width of 40 fs was used. In this work [5], experimental tests demonstrated that the detector response in terms of charge and spatial resolution depends on the applied gain. Then, gas mixture, gain voltage, and threshold level are the main parameters to set the optimal working point according to the flux and energy of the soft X-photons coming from the plasma source. In the present work, the first preliminary measurements of soft X-rays on VEGA-2 laser facility will be shown. In VEGA-2, a photon flux higher than the ECLIPSE laser facility [6] was expected, hence the response of GEMpix to a higher photon flux has been tested, while the application of a filter mask shows how these measurements are correlated to the plasma temperature.

## 2 First results on VEGA-2 laser facility

### 2.1 Experiments at VEGA-2

VEGA-2 is a laser facility at Centro de Laseres Pulsados (CLPU) in Salamanca (Spain) [7]. The laser works at the wavelength of 800 nm with the focal spot on target which can range from few μm



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to tens of µm. It can provide a maximum laser power of more than 6 J with a pulse time width of 30 fs. During our experimental campaign, it worked at a power of about 6.5 J with the focal spot size on target of 21.6 µm. We participated in the experiment conceived to study the generation of very strong shock waves by fs lasers. The main goals of the experiment were the study the blast wave dynamics in the solid and the measure of the hot electrons and the temperature of warm dense matter. Many of these phenomena are related to the plasma temperature and GEMpix diagnostic has been tested in order to validate its application as soft X-rays detector to estimate plasma temperature. Figure 2 reports a scheme of the experimental setup of the diagnostics.

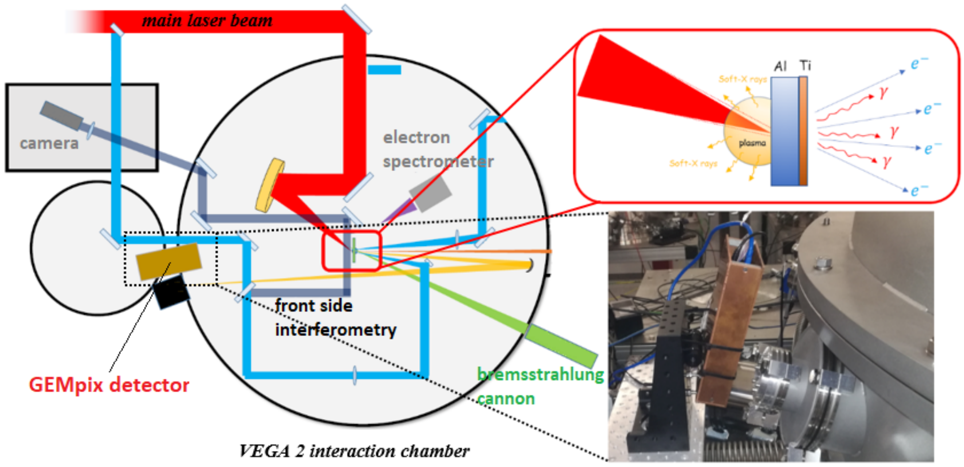


**Figure 2**. A schematic layout of the experimental set-up. The main diagnostics for the experiment have been highlighted.

The GEMpix detector has been mounted outside the interaction chamber on a port placed on the same side of the laser beam, in order to detect the X-ray emitted radiation from the ablated plasma. The port has a 100 µm mylar window with a diameter of 10 mm. During the experimental campaign, the targets were realized with three different materials: aluminum, parylene, and polypropylene with different thicknesses. In this paper, we report results obtained for 10 mm thick parylene targets. All the targets have a 2 mm thick layer of titanium on the opposite side respect to the impinging laser. For these targets, GEMpix was equipped with three absorbers in order to make an estimate of the plasma electron temperature. Two filters have the same thickness (100 µm) because the area of the Mylar window corresponding to one chip was damaged and consequently it was necessary to put the same filter thickness for comparison. The third installed filter has a thickness of 200 µm.

### 2.2 Soft X-ray measurements

As described in section 1.1, GEMpix Front End Electronics (FEE) is based on four Timepix chips which usually have a systematic difference in the responses due to the different gains and/or thresholds of the electronics connected to the pixels. In order to correct these effects and to obtain a uniform response, a selection of four circular areas on the four chips has been performed to study signal shifts between chips and to adjust systematic differences. Figure 3a shows an image coming of the soft X-rays coming from a 10 µm thick parylene target.



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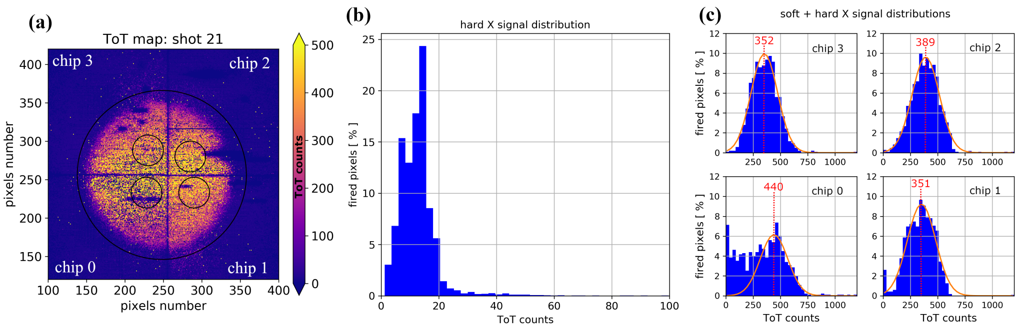


**Figure 3**. a) GEMpix measured signal for shot # 21 in which a 10 mm target of parylene was hit by 6.5 J power laser beam; b) distributions for all the pixels outside the main spot as highlighted in a); c) charge distributions for all the pixels inside the selected circular areas

In figure 3c, the distributions for the charge in the four selected circular regions are reported together with Gaussian fits and, as can be observed, there are systematic shifts between the obtained peak values. Outside the main central image, a background distribution with a lower charge has been observed. Because this is produced outside the port window, it is a signal due to hard-X and gamma rays. The charge contribution coming from these high energy photons has been subtracted from the soft-X signal, as explained in the next section. It has been observed also that different power densities correspond to different spectra in ToT (and in photon energy). Depending on the target and laser beam conditions, for some shots a warmer plasma can be produced and a corresponding higher charge is measured due to a higher photon flux and higher energy X-rays.

VEGA-2 (hundreds of TW in about 30 fs) is one hundred times more intense with respect to ECLIPSE laser. In this case, a gain voltage of 600 V has been applied (200 V for each GEM foil), a value lower than the one applied for the ECLIPSE facility (900 V). For the regions as defined in figure 1 (drift, transfer1, transfer2 and induction gaps) voltages are set in order to obtain the standard applied electric fields: 3 kV/cm for the first three regions and 5 kV/cm for the induction gap. Since the power released by VEGA-2 is higher than the one by ECLIPSE, a corresponding higher X-rays flux was expected. A gain voltage of 900 V was not possible because the corresponding charge was too high for the readout preamplifier and all the irradiated pixels were saturated. In general, active detection systems can suffer some disturbances due to the intense electromagnetic pulse (EMP) produced by the laser-target interaction. Often these disturbances occur as heavy electronic noise, unwanted stops of data acquisition or a total stop of readout electronics. In the present case, our detector has not experienced this type of problems and worked correctly. In addition, a triple-GEM detector like this, shows a negligible sensitivity to $\gamma$ and HXR (in this case, higher than 20 keV) because only a fraction of the photon energy is released in the active gas layer with respect to the soft X-rays photons. The contribution due to the higher energy photons can be further reduced applying a given threshold level. In the present case, a minimum threshold was set in order to cut only the electronic noise and not the signal due to high energy photons which have a negligible contribution.

### 2.3 Charge measurements and plasma temperature

In this experiment, an estimation of plasma temperature was required. At the moment, our diagnostic shows excellent functionality in terms of immunity to the EMP and charge measurements. As shown

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in section 2.2, the distributions of ToT counts per pixel are localized on given values. In addition, the mean value and the sum of ToT counts in 2 sigmas of the gaussian fit, depends on the flux and energy spectrum of the incident photons. For a given plasma temperature, a characteristic soft X-ray spectrum is expected. In figure 4, the spectra reaching the GEMpix for two possible temperature values are plotted.

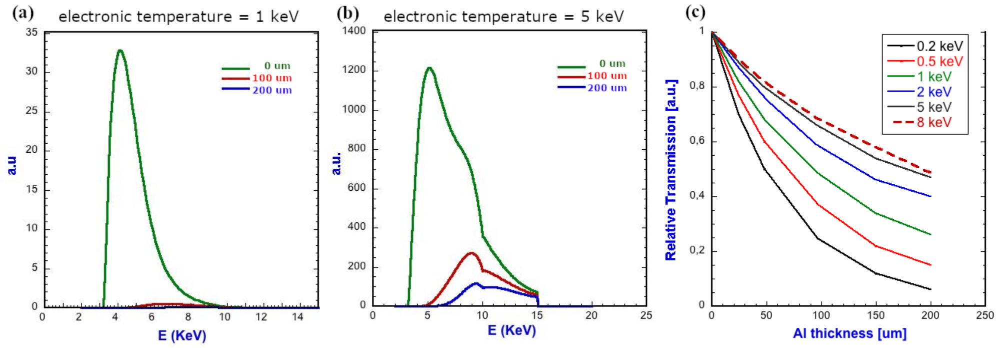


**Figure 4**. a) and b) expected softX-rays spectra produced by plasma with two different temperatures; c) the corresponding aluminum filter transmission curves for different plasma temperatures, as obtained from a theoretical calculation.

The temperatures from 1 to 5 keV represent the typical expected values in the present experiment. When the two aluminum filters of 100 and 200 μm are applied, the spectra change depending on the expected temperature. As a consequence, the ratio between the energy released in the GEMpix gas active volume with an without a given aluminum filter has a trend which depends on the X-ray temparature spectrum, as shown in figure 4c. GEMpix detector provides ToT measure of the charge released by $n(E)$ photons of energy $E$ that interact in a time width lower than 1 ns. Considering the minimum acquisition time window of GEMpix readout electronics of 1 μs, it can be assumed that the $n$ photons interact simultaneously and the charge $Q_{\mathrm{px}}$ detected per pixel is given by

$$Q_{\mathrm{px}} = G \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} (E/w)\, en\,(E)\, dE$$

where $G$ is the effective gain, $E$ is the photon energy in the spectrum which ranges from $E_{\mathrm{min}}$ to $E_{\mathrm{max}}$, and $w$ is the needed energy to produce an electron-ion couple, and $e$ is the electron's charge. The ToT distributions on all the pixels in the defined circular areas per chip provide a measure of the charge for a given input spectrum. When a filter is applied, the spectrum is modified and a different charge distribution is expected. As the response is proportional to the charge $Q_{\mathrm{px}}$, a measure of the charge per pixel is also sensitive to the plasma temperature (see figure 5).

In order to quantify the detector response as a function of the plasma temperature, the following parameters have been considered from the experimental ToT distributions where a gaussian fit has been performed: the sum of all ToT counts $N_p$ up to 2 times the gaussian sigma and the sum of all non-zero pixels $N_v$ in the same range are used to define the following ratios for the three applied filters:

$$\frac{R_{0,1,3}}{R_2} = \frac{\left(N_v/N_p - BKG\right)_{0,1,3}}{\left(N_v/N_p - BKG\right)_2}$$



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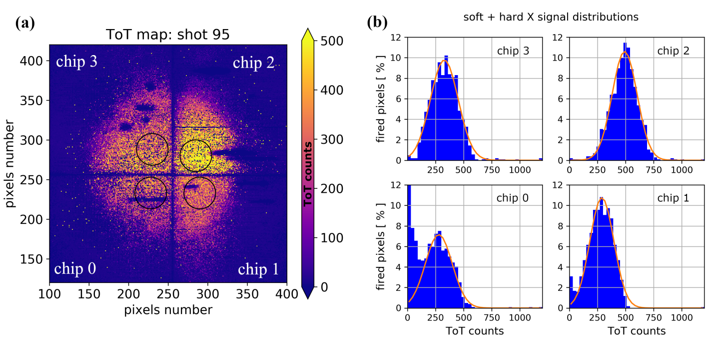


**Figure 5**. GEMpix signal after the three filters before the detector window: the upper right chip has no filters.

where indices 0, 1, 2 and 3 refer to the chip number (as in figure 5a) and $BKG$ is calculated as the mean value of the ToT distribution outside the spot area for each chip area. Because the filters used for chip areas 1 and 3 have the same thickness, the average value is calculated. In addition, these ratios have been calculated also for data without filters and the obtained values are used as corrective factors for the ratios obtained with filters. Figure 6 shows a plot of the two ratio values corresponding to the two-filter thicknesses shot by shot.

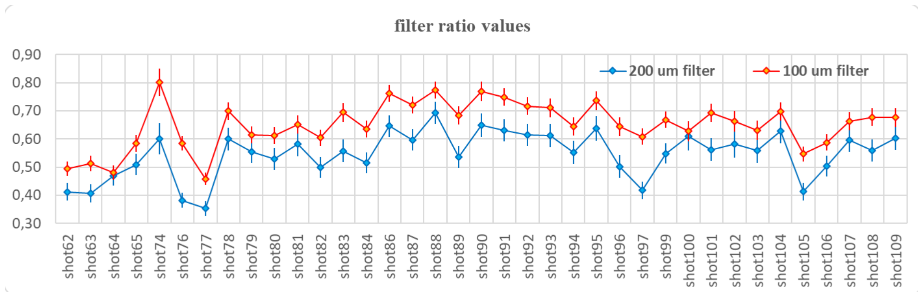


**Figure 6**. Two estimated absorption ratios shot by shot with a 10 mm target of parylene and a laser power of about 6.5 J.

As expected, the ratio corresponding to a 100 µm filter is systematically higher than the ratio corresponding to 200 µm filter. A lower ratio for 100 and 200 µm suggests a lower temperature spectrum, because the applied filters reduce more the number of photons in the transmitted spectrum. For some shots, the difference between the two values is smaller and this can be correlated to a higher energy spectrum, as can be observed from the theoretical curves in figure 4c This preliminary analysis provides some good directions for the use of GEMpix detector for the estimation of the plasma temperature.

## 3 Conclusions

A preliminary work has been realized on the VEGA-2 laser facility and the first results are promising. The GEMpix detector is working properly also on a high-power laser facility (low noise and good signal acquisition). SXR measurements show a good matching with the laser target interactions.



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In addition, the use of filters allowed demonstrating a correlation of the signal with the plasma temperature, an interesting data that will be further studied in the future.

Recently, further improvements have been introduced to the GEMpix detector: a mask with twelve holed filters is ready to be used in the next experimental campaign. Four holes will be used to calibrate the response of the chips, while the remaining will be used with the application of a sequence of aluminum filter with increasing thickness. This preliminary work shows that GEMpix detector can represent a valid active diagnostic for soft-X rays. In the future, further experimental tests are planned in order to compare its performances with the standard diagnostic methodologies: Image Plate, CCD, and Multi-Channel-Plate. The present results demonstrated some very useful characteristics of GEMpix detector: good sensitivity, a large dynamic range, spatial resolution, absence of noise thanks to the adjustable thresholds and in real-time measurements.

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