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# Serial data acquisition for the X-ray plasma diagnostics with selected GEM detector structures

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ABSTRACT: The measurement system based on GEM - Gas Electron Multiplier detector is developed for X-ray diagnostics of magnetic confinement tokamak plasmas [1,2]. The fast and accurate mode of the serial data acquisition is applied for the dynamic plasma diagnostics. The ADC (Analog to Digital Converter) samples triggered by the corresponding detector current are acquired independently for the measurement channels. The charges are calculated within the defined time window for the activated channels. Data are synchronized with the specified ADC frequency and discrete intervals of charge acquisition are the multiples of the sampling time. Resulting data samples are processed by FPGA circuits (Field-Programmable Gate Array) and form the table of chronological triplets: [charge value, channel number, triggered time]. Data packages are loaded sequentially to the DDR memory and finally are conveyed to the PC. The charge cluster is identified as a set of adjacent pixel charges in the area of the detector. Only regular clusters without any defects are considered for histogramming. Regular clusters are counted in the four dimensional space determined by the planar position, charge value (energy) and time intervals. Final data processing is presented in any 2-D cross-section for selected range of position, charge and time interval. Several detector structures with single-pixel channels and multi-pixel (directional) channels are considered for two-dimensional X-ray imaging. Radiation source properties are measured by the basic cumulative characteristics: the cluster position distribution and cluster charge value distribution corresponding to the energy spectra.

- KEYWORDS: GEM; Pixelated detectors; X-ray detectors; Plasma diagnostics - interferometry, spectroscopy and imaging.

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## Contents



## 1. Introduction

Measuring Soft X-Ray (SXR) radiation (0.1-20 keV) of magnetic fusion plasmas is a standard way of accessing valuable information on particle transport and magnetic configuration. This characteristic radiation provides accurate information on the crucial plasma parameters such as impurity concentration, ion temperature, and the toroidal rotation velocity. The GEM-based detector is proposed for SXR tomography applying Bragg crystal spectroscopy for effective monitoring the impurity with tungsten focused measurement [3,6,7,10]. The X-ray T-GEM detector is based on collection of electrons created by direct ionization within the gas (Ar + $CO_2$) through application of electric field that initiates an electron avalanche (Figure. 1). The large electric field in small holes in a thin polymer sheet causes the avalanche inside of these holes. Three layers of electrodes powered by high voltage result in reproduction of the electrons and amplification of the total charge of the cluster. The multiplied space charge, which is injected to the final segment of the detector, so-called induction gap, and collected on the multi-pixel plane, generates current anode signals detected by the electronics.

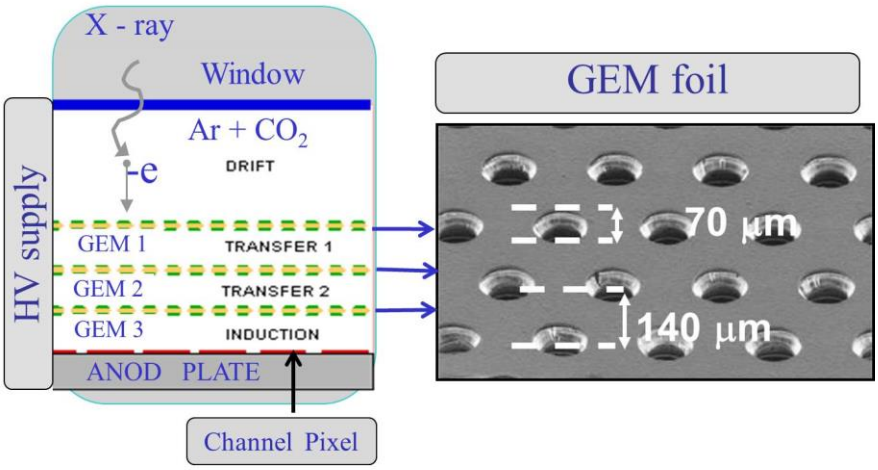


Figure 1. Cross section of the GEM detector arrangement (left) and GEM foil structure (right).

## 2. Multi-channel measurement system

The multi-channel measurement system based on GEM detector is developed for X-ray diagnostics tokamak plasmas. Energy characteristics of the X-ray source correspond to the charge and position of the electrons cluster in GEM detector. Pulse current signal from the detector pixel is amplified and shaped and by the filter. Analog signal is sampled with 77.7 MHz frequency and digitized by 10 bit resolution ADC converter. The current signals generated by the detector carry all information required for the energy estimation and position reconstruction for X-rays. The focal measuring issue is the cluster charge identification by its value and position estimation. Cluster charge value distribution corresponds directly to the energy spectra of X-ray source. Cluster charge position distribution corresponds to the energy for Bragg diffraction spectroscopy. These characteristics are crucial for the tokamak plasma diagnostics. The multi-channel setup is designed for estimation of the energy and position of an X-ray source. In the measurement GEM based system the serial data acquisition is applied for the dynamic plasma diagnostics. All ADC samples exceeding the trigger level are acquired independently for each measurement channel. The FPGA based system performs the basic functions of data processing: data receiving, signals selection, charge estimation and memory operation [4,5,9,11]. The charges are calculated within the time window of 20 signal samples for the activated channels. Resulting serial data samples form the table of chronological triplets: [Q - charge value, P - channel number, T - triggered time]. Data packages are loaded sequentially to the DDR SDRAM memory and finally are conveyed to the PC which performs the basic functions of data processing: events selection, clustering, histogramming. MATLAB software package is the universal interface providing user control, communication, diagnostics, data processing functions, and imaging results.

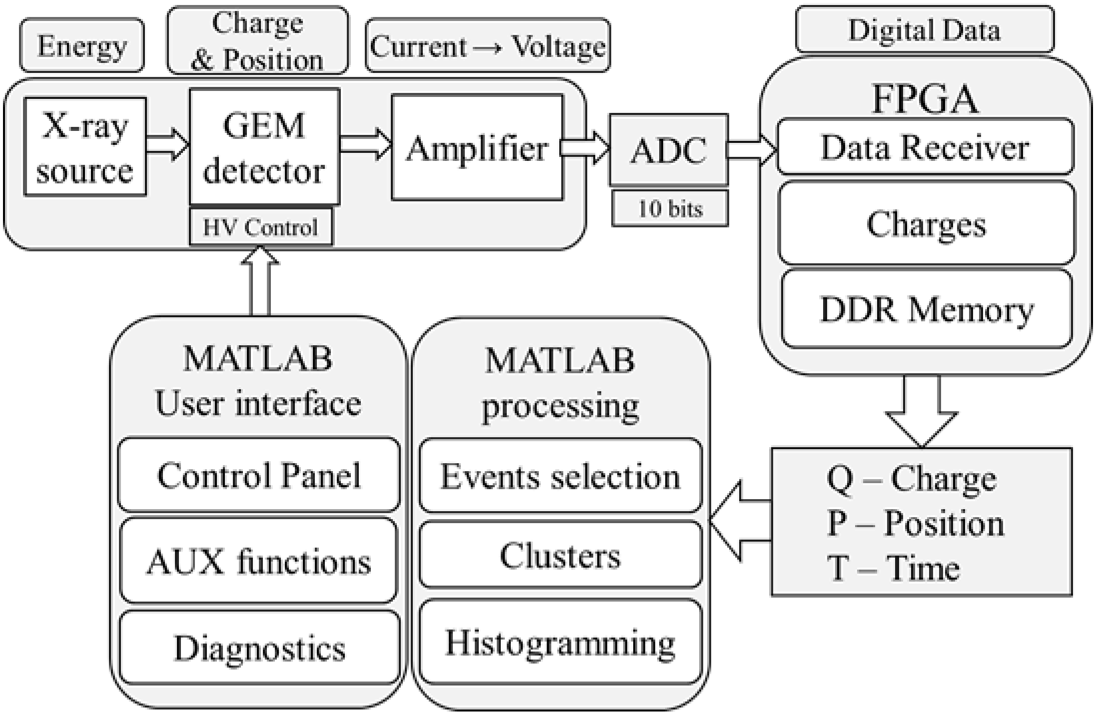


Figure 2. The block diagram of the multichannel measurement system.

## 3. Serial data acquisition

The serial data acquisition is applied to obtain spatial and time characteristics for X-ray radiation. All ADC samples exceeding the trigger level are acquired independently for each measurement channel. The acquired signal is analyzed within 40 sampling cycles (Figure 3). The first ten samples determines the offset level. The charge value is calculated as the sum of the next 20 signal samples. The last ten samples check overlapping signals. Distorted signals (overlapped or saturated) are marked by the special charge value.

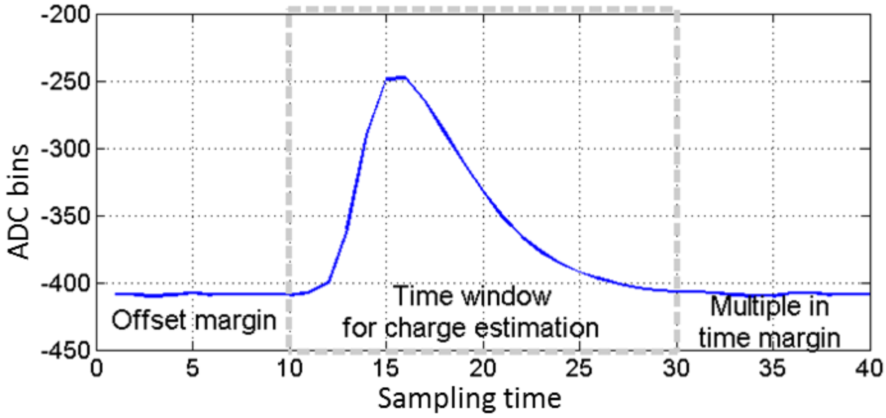


Figure 3. The regular ADC signal represented by the 40 acquired samples.

Resulting serial data samples form the table of chronological triplets: [Q - charge value, P - channel number, T - triggered time]. All channels corresponding to the given cluster are triggered in the same clock time, called the event time, or some of them are delayed by one cycle only. The bunches of coinciding clusters, corresponding to the given event time, create separated events which are selected sequentially for the cluster identification. The particular event requires investigation of the charge planar distribution for the specified detector structure. The charge cluster is identified within the event as a set of adjacent pixel charges exceeding the given noise level. The channel charge contributes to the total counts for the given pixel according to its charge share in the cluster (fraction of the cluster) .

Several technical characteristics are considered to verify data acquisition reliability. Data time structure is represented by the samples corresponded to the points in the space (time, charge value, channel position). Typical constellation of samples for the single laser shot activated the Cu target is displayed in figure 4. It shows that plasma emission in the target lasts ~47 clock cycles what matches with the time resolution ~0.6 us of the single measurement channel for data acquisition. The red dots relate to the distorted signals which result loss of corresponding clusters for histogramming.

The time structure of events frequency is presented by the distribution of discrete gaps between sequential samples (Figure 5). The highest counts values for zero and one gap correspond mostly to the dependent signals for the same cluster. For the condition: $1 <$ *time interval* $< 50$, the chart corresponds to the Poisson distribution of independent events.

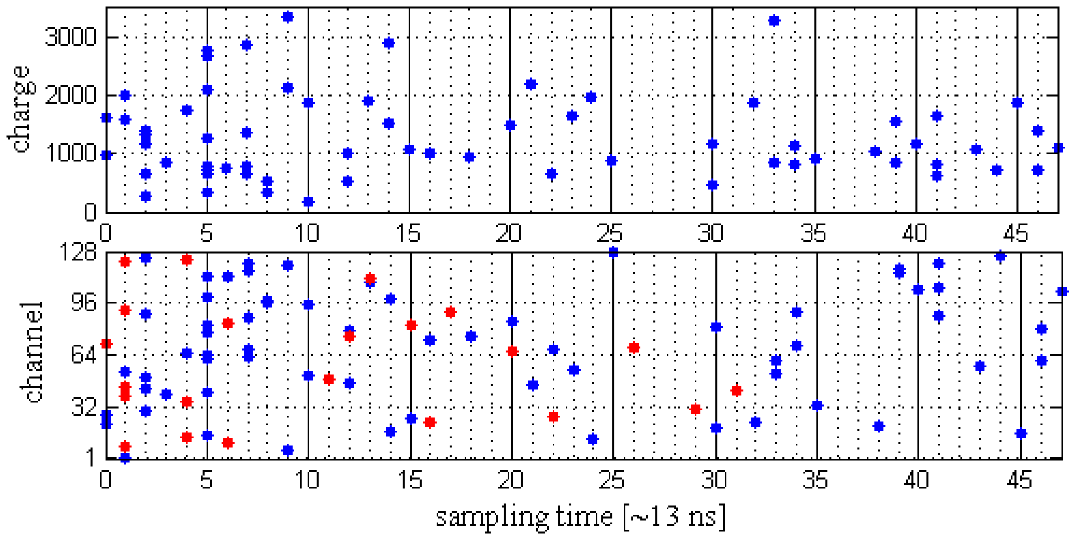


Figure 4. Data time structure for high flux of X-ray emission from Cu target activated by the laser shot.

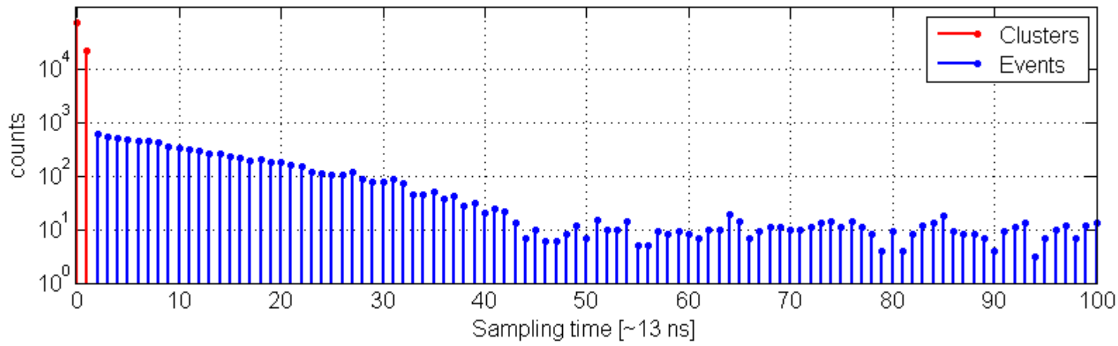


Figure 5. Sampling gaps distribution for 392171 samples of data acquisition for $^{55}Fe$ source.

## 4. Detector array structures

Generally two kind of array structures are considered for X-ray 2-D imaging [8,10]. In the detector structure with single-pixel channels the measurement channel is connected to the one pixel only and many channels is required for a good spatial resolution. So, alternative solution is detector structure with multi-pixel channels where one channel connects many pixels lying on the given direction (axis) and combination of two or three channels determines the cluster position.

### 4.1 Hexagonal array structure

Two dimensional GEM detector with hexagonal structure is applied as 128-channels sensor. The hexagonal array is transformed to the rectangle array for the performance of the cluster charge planar distribution. The single hexagonal corresponds to the two rectangles (Figure 6).

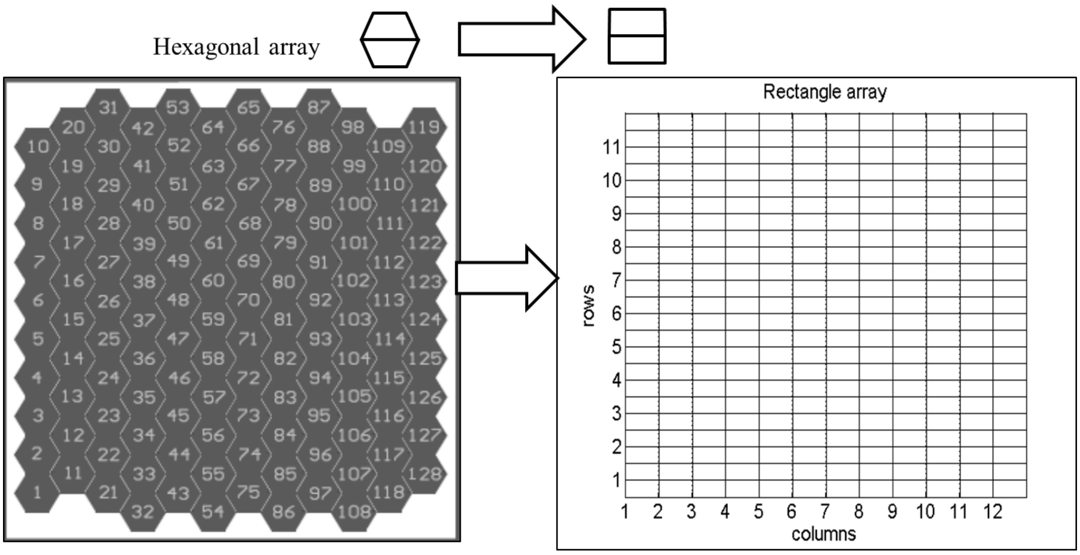


Figure 6. Hexagonal array structure transformed to the rectangle array.

The clusters for the given event are identified sequentially pixel by pixel limited within the rectangle. The cluster charge is scattered within few pixels. Each pixel corresponds to the selected part of the detector area. The position of the cluster charge is considered to be scattered according to the relative values of the pixel charges. The pixel shares from all events are cumulated respectively for sequential cluster values and time intervals. Consequently, the cluster distribution is determined by the counts in the 4-dim histogram array H(*y*-row, *x*-column, *Q*-cluster charge, *T*-time). Radiation source properties are considered by the basic cumulative characteristics: cluster charge value distribution and cluster position distribution within the assumed time intervals. Figure 7 shows characteristics for the $^{55}Fe$ reference source for the hexagonal detector structure for 30 minutes data acquisition time.

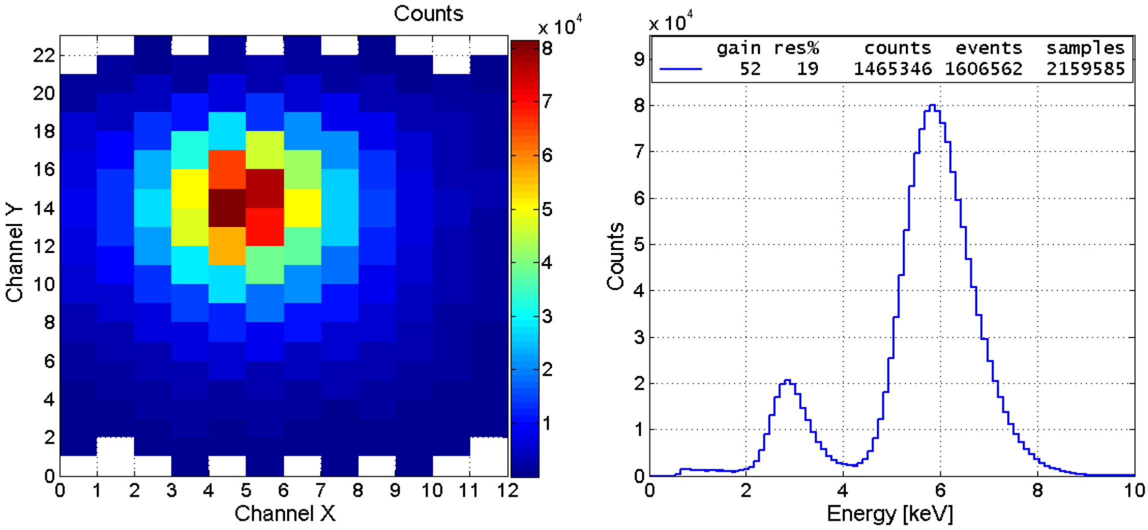


Figure 7. The GEM detector characteristics for the $^{55}Fe$ reference source for hexagonal array structure: planar distribution (left), energy spectra (right).

### 4.2 XY array structure

Two dimensional GEM detector based on two-axis coordinate system XY [64×64] consists of 4096 pixels connected with 128 measurement channels is applied as a high resolution planar sensor (Figure 8). The cluster shares are identified for succeeding channels and the resultant charge value and position are estimated for the partial clusters for each coordinate XY respectively. The reduced data for the given event create Cartesian product X×Y for all possible position doubles (*x*, *y*). For the independent coordinates (X, Y) only single cluster event can be identified uniquely. Consequently, for a high intensity radiation the multi-hit events data are lost for histogramming. Figure 9 shows cumulative characteristics for two $^{55}Fe$ reference sources with different intensity for 1000 seconds data acquisition time.

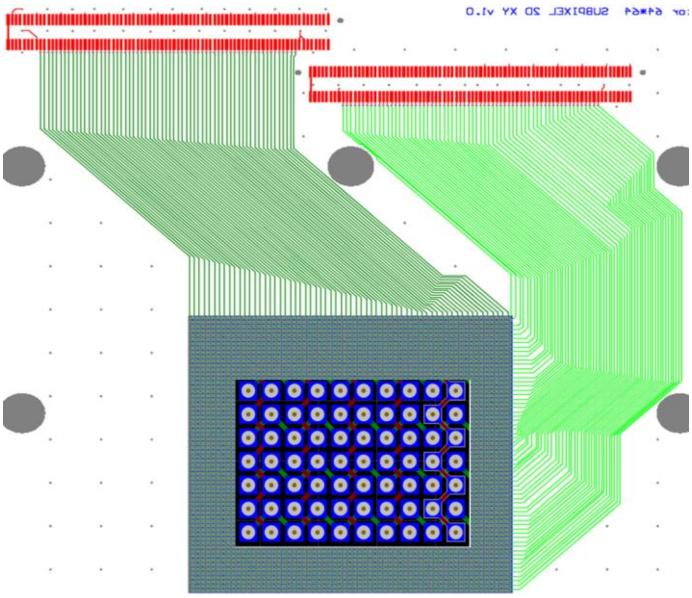

Figure 8. The board layout for XY array structure.

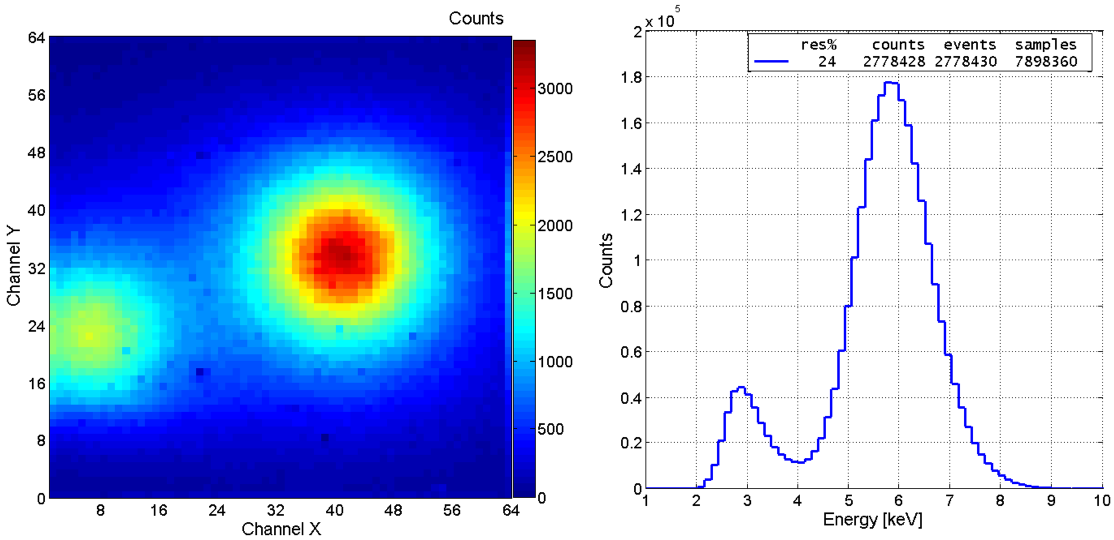


Figure 9. The GEM detector characteristics for two $^{55}Fe$ reference sources with different intensity for XY array structure: planar distribution (left), energy spectra (right).

### 4.3 UXV array structure

Two dimensional GEM detector based on three-axis coordinate system UXV [64×64×64] with 192 measurement channels is applied as a high resolution planar sensor for multi-hit events (Figure 10). The detector structure consists of 18432 triangle sub-pixels which compose the hexagonal net. The triangle sub-pixels are connected along three symmetrical directions and form coordinate paths corresponding to the measurement channels. The space resolution of the detector structure is specified by a triangle pixel but the space accuracy is limited by a compound hexagonal which is determined by three coordinates ($u$, $x$, $v$). The UXV setup determines 3072 compound effective hexagonal pixels.

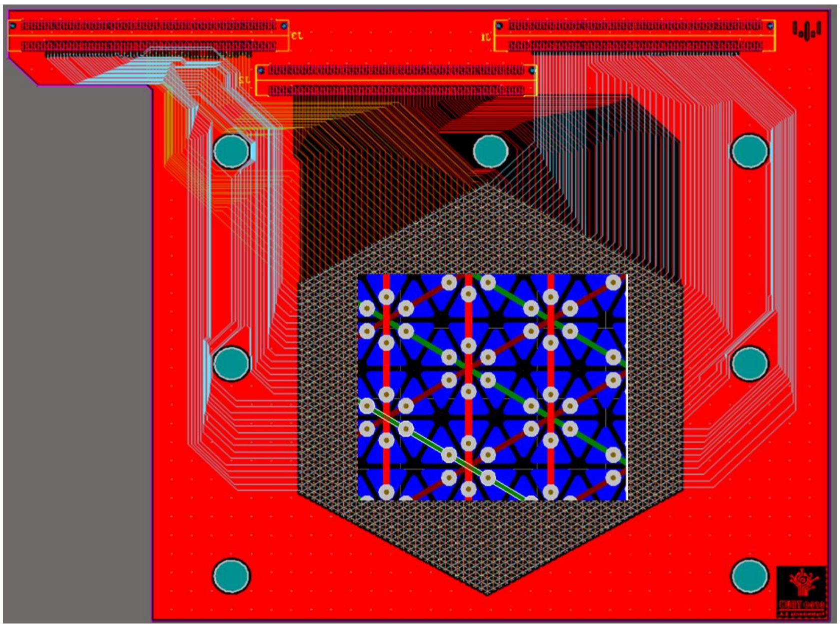

Figure 10. The board layout for UXV array structure

There are two types of hexagonal center position:

1) at coordinate paths intersection according to the relation $u + v - x - 32 = 0$

2) inside coordinate paths triangle according to the relation $u + v - x - 32 = \pm 1$.

Consequently, the hexagonal is identified by the triplet ($u$, $x$, $v$) on condition that: $|u + v - x - 32| < 2$.

In the purpose of the digital imaging the UXV coordinate system is transformed to the hexagonal part of the YZ [128×192] array. The triangle pixel is mapped to the rectangle. The hexagonal center corresponding to the triplet ($u$, $x$, $v$) is converted to the point determined by the YZ coordinates: $y = u - v + 64$ and $z = u + v + 2x - 33$.

The cluster identification is performed sequentially for the individual events corresponding to the serial data acquisition. Firstly, the cluster shares are identified for succeeding channels for each coordinate UXV respectively. Next, the resultant charge value and position are estimated for the recognized partial clusters for each coordinate UXV respectively. Consequently, the reduced data for the given event create Cartesian product U×X×V for all possible position triplets ($u$, $x$, $v$) in the case of multiple clusters. Potential cluster triplets ($u$, $x$, $v$) correspond to the hexagonal position and are selected by the condition: $|u + v - x - 32| < 2$. Possible false cluster triplets for repetitive coordinates values are identified and removed in cycle of two steps. In the first step the necessary condition separate the part of the correct triplets. In the second step the sufficient condition removes the part of the false triplets. The cycle can be repeated but for some few arrangements of multi-hit events not all clusters can be identified uniquely. A few smaller clusters are determined by two coordinates only.

Cluster charge components are summarize to estimate the total cluster charge for the given triplet. Finally, the cluster charge is uniformly assigned to the area of the YZ array corresponding to the given hexagonal. Finally, the cluster distribution is determined by the counts in the 4-dim histogram array H(*y*-row, *z*-column, *Q*-cluster charge, *T*-time). Radiation source properties are considered by the detector cumulative characteristics: cluster counts planar distribution and cluster charge value distribution (Figure 11).

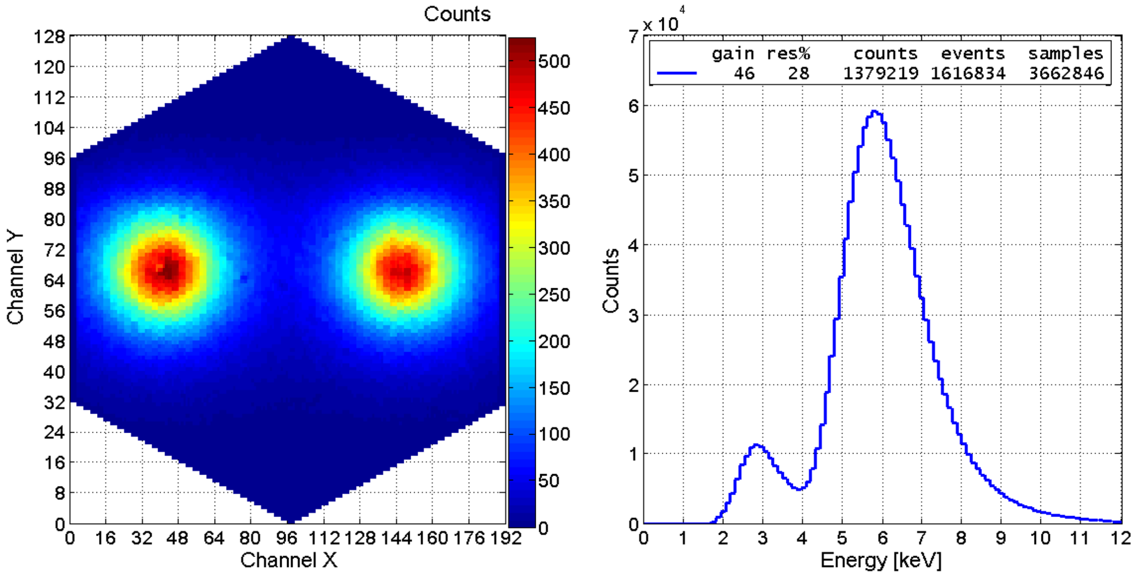


Figure 11. The GEM detector characteristics for two $^{55}Fe$ reference sources for UXV array structure: planar distribution (left), energy spectra (right) .

## 5. Summary

The multichannel measurement system based on GEM - Gas Electron Multiplier detector and essential data processing for X-ray energy and position recognition has been presented. The serial data acquisition has been verified for $^{55}Fe$ reference sources and high intensity X-ray emission from metal targets activated by the laser. Four dimensional histogramming enables comprehensive analyzing in planar, energy and time domain for the X-ray characteristics. Detector structures with single-pixel channels and multi-pixel (directional) channels have been considered for two-dimensional X-ray imaging. The hexagonal array structure is intended for stationary and fast dynamic X-ray detection but limited by the relatively low space resolution. XY array structure has high planar resolution for stationary only X-ray detection. UXV array structure has high planar resolution and multi-hit detection possibility with rather complex data analyzing.

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