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. The paper is focused on the measurement subject and describes the fundamental data processing to obtain reliable characteristics (histograms) useful for physicists. The required data processing have two steps: 1 — processing in the time domain, i.e. events selections for bunches of coinciding clusters, 2 — processing in the planar space domain, i.e. cluster identification for the given detector structure. So, it is the software part of the project between the electronic hardware and physics applications. The whole project is original and it was developed by the paper authors. The previous version based on 1-D GEM detector was applied for the high-resolution X-ray crystal spectrometer KX1 in the JET tokamak. The current version considers 2-D detector structures for the new data acquisition system. The fast and accurate mode of data acquisition implemented in the hardware in real time can be applied for the dynamic plasma diagnostics. Several detector structures with single-pixel sensors and multi-pixel (directional) sensors are considered for two-dimensional X-ray imaging. Final data processing is presented by histograms for selected range of position, time interval and cluster charge values. Exemplary radiation source properties are measured by the basic cumulative characteristics: the cluster position distribution and cluster charge value distribution corresponding to the energy spectra.

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KEYWORDS: Pattern recognition, cluster finding, calibration and fitting methods; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Data acquisition concepts; Plasma diagnostics - interferometry, spectroscopy and imaging
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. Radiation in this wavelength range provides accurate information on the crucial plasma parameters such as impurity concentration, ion temperature, and the toroidal rotation velocity. GEMs are one of the class of micropattern gas detectors — MPGD [1, 2]. Soft X-ray imaging of the NSTX — National Spherical Tokamak eXperiment core plasma by means of an MPGD pinhole camera is described in [3]. The GEM-based detector is proposed for SXR tomography applying Bragg crystal spectroscopy for impurity measurements especially focused on tungsten emission, which is mainly in the Soft X-ray spectral range [4, 6–8, 11]. The X-ray T-GEM detector is based on collection of electrons created by direct ionization within the gas inside the detector (Ar + CO₂) (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

![Figure 1. Cross section of the GEM detector arrangement (left) and GEM foil structure (right).](image-url)
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.

2 Multi-channel measurement system

The multi-channel measurement system based on GEM detector is developed for X-ray diagnostics tokamak plasmas (figure 2). The system is modular up to 256 measurement channels. Hardware description of the system can be found in [5, 10, 12]. The multi-channel setup is designed for estimation of the energy and the position distribution of an X-ray source. Pulse current signal from the detector pixel is amplified and shaped by the filter. Analog signal is sampled with 77.7 MHz frequency and digitized by 10 bit resolution ADC — Analog to Digital Converter. The focal measuring issue is the cluster charge identification by its value and position estimation. The cluster charge can be spread over several pixels. 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. In the GEM based measurement 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 — Field-Programmable Gate Array based system performs the basic functions of data processing: data receiving, signals selection, charge estimation and memory operation. The charges are calculated within the time window of 20 ADC samples for the activated channels. Resulting serial data 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 (Double Data Rate Synchronous Dynamic

![Figure 2](image). The block diagram of the multichannel measurement system.
Random Access 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.

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 in the middle time window. The regular signals fit in the time window. 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.](image)

Resulting serial data samples form the table of chronological triplets: \([Q — \text{charge value}, P — \text{channel number}, T — \text{triggered time}]\). Data packages are loaded sequentially to the DDR memory and finally are conveyed to the PC. 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 bunch of coinciding clusters, corresponding to the given event time, create the separated event. So, the samples in the event can be moved mutually by no more than one cycle only. 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). 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 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 a single laser shot activated Cu target is...
displayed in figure 4. The repetition of laser shots is 1 Hz. The plasma emission in the target lasts \( \sim 47 \) clock cycles what matches with the time resolution \( \sim 0.6 \) 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.

Data frequency structure is represented by the distribution of discrete gaps between sequential samples for the \(^{55}\text{Fe}\) reference source (figure 5). The highest counts values for zero and one gap correspond mostly to the dependent signals for the same cluster, where the samples can be moved mutually by no more than one cycle only. For the condition: \( 1 < \) time interval < 45, the chart corresponds to the Poisson distribution of the source decay events. The uniform distribution disclosed for higher gaps corresponds to the noise background.

Figure 4. Data time structure for high flux of X-ray emission from Cu target activated by the selected laser shot. The red dots relate to the distorted signals.

Figure 5. Sampling gaps distribution for 2382685 samples of data acquisition for \(^{55}\text{Fe}\) source.
4 Detector array structures

Generally two kind of array structures are considered for X-ray 2-D imaging [9]. In the detector structure with a single-pixel sensors the measurement channel is connected (wired) to the one pixel only and many channels is required for a good spatial resolution. So, alternative solution is detector structure with multi-pixel sensors where one channel connects (wires) many pixels lying on the given direction (axis). The cluster position is determined if all independent directions (coordinates) are activated. All presented below detector structures have similar dimension enveloped by ~ 10 cm square.

4.1 Hexagonal array structure

Two dimensional GEM detector with hexagonal array is applied as a single-pixel sensors structure with 128 channels. The hexagonal array is transformed to the rectangle array for the efficient data analysis of the cluster charge planar distribution in the Cartesian coordinates. The single hexagonal corresponds to the two rectangles (figure 6).

![Hexagonal array structure](image)

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

The clusters for the given event are identified sequentially pixel by pixel enclosed by the rectangle. The cluster charge can be 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. The lower energy peak is termed the argon escape peak. The
hexagonal array structure is intended for stationary and fast dynamic X-ray detection but the space resolution is limited directly by the channels number.

4.2 XY array structure

Two dimensional GEM detector based on two-axis coordinate system XY \[64 \times 64\] consists of 4096 pixels connected with 128 channels is applied as a high resolution planar structure with multi-pixel sensors (figure 8). The cluster is spread in the rectangle determined by the compact set of coordinate values \([X]\) and \([Y]\). The position of the cluster charge is considered to be scattered according to the

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

Figure 8. The board layout for \(X\) — brown, \(Y\) — green, array structure (zoomed area in the middle).
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).

relative values of the pixel charges for each pair $(x, y)$. 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.

4.3 **UXV array structure**

Two dimensional GEM detector based on three-axis coordinate system $UXV$ [$64 \times 64 \times 64$] with 192 channels is applied as a high resolution planar structure with multi-pixel sensors 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.

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:

$$|u + v - x - 32| < 2.$$

The cluster identification is performed sequentially for the individual events corresponding to the serial data acquisition. The cluster can be spread over several parallel consecutive channels for
Figure 10. The board layout for $U$ — green, $X$ — red, $V$ — brown array structure (zoomed area in the middle).

the same coordinate. The channel with the greatest charge value is taken as the resultant position for the given coordinate. The sum of all partial charges is taken as the resultant charge value for the given coordinate. Consequently, the reduced data for the given event create Cartesian product $U \times X \times V$ for all possible position triplets $(u,x,v)$ in the case of multiple clusters. Potential cluster triplets $(u,x,v)$ are selected by the condition: $|u+v-x-32| < 2$ correspondingly to the hexagonal position. Possible false cluster triplets for repetitive coordinates values are identified and removed, 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.

In the purpose of the digital imaging the $UXV$ coordinate system is transformed to the hexagonal part of the $YZ$ $[128 \times 192]$ array (figure 11 — left). 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 $z = u+v+2x-33$.

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. 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).

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

analysis in planar, energy and time domain for the X-ray characteristics. Detector structures with single-pixel sensors and multi-pixel (directional) sensors have been considered for two-dimensional X-ray imaging. Single-pixel sensors structure is intended for stationary and fast dynamic X-ray detection but space resolution is limited by the channels number. $XY$ array structure has high planar resolution for stationary only X-ray detection. $UXV$ array structure has high planar resolution and multi-hit detection capability with rather complex data analyzing.

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