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Coinciding signals estimation for high flux radiation in GEM detector for fusion plasma imaging

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The measurement system based on GEM - Gas Electron Multiplier detector is developed for X-ray diagnostics of magnetic confinement tokamak plasmas. The multi-channel setup is designed for estimation of the energy and the position distribution of an X-ray source. The main measuring issue is the charge cluster identification by its value and position estimation. High flux radiation cause the problem of coinciding signals for cluster charge identification. The amplifier with shaper determines time characteristics and limits the pulses frequency. The essential assumption is that overlapping signals can be reconstructed if primary GEM pulses do not coincide. The ending tail of the signal can be restored for the given electronics characteristics. The proposed algorithm can be apply iteratively for series of superimposed pulses. Separation of coincided signals was introduced and verified for simulation experiments. On line separation of overlapped signals was implemented applying the FPGA technology with relatively simple firmware procedure. Representative results for reconstruction of coinciding signals are demonstrated. Radiation source properties are presented by the histograms for selected range of position, time intervals and cluster charge values corresponding to the energy spectra.

Keywords: GEM; Pixelated detectors; X-ray detectors; Charge cluster; Plasma diagnostics.

1. Introduction

The measurement system based on GEM - Gas Electron Multiplier detector is developed for X-ray diagnostics of magnetic confinement tokamak plasmas [1,2]. 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 a 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-strip-pixel plane, generates current anode signals detected by the electronics.

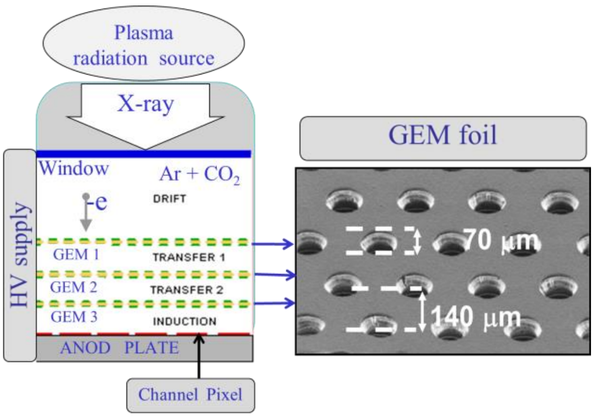

Fig. 1. Cross section of the GEM detector structure (left) and GEM foil structure (right).

2. Multi-channel measurement system

The multi-channel measurement system based on GEM detector is developed for SXR diagnostics tokamak plasmas [3]. The system is modular up to 256 measurement channels (Fig. 2). X-ray photon energy is converted to the charge in the given position of the detector. The charge cluster can be spread over several detector pixels. Pulse current signal from the detector pixel is amplified and shaped by the filter. The FPGA—Field-Programmable Gate Array based system—performs the basic functions of data processing in a real time: data receiving, signals selection, charge estimation, and memory operation [4]. Data packages are loaded sequentially to the memory and finally are conveyed to the PC, which performs the basic functions of data offline processing: events selection, clustering, histogramming. MATLAB based software package is the universal interface providing user control, communication, diagnostics, data processing functions, and results imaging.

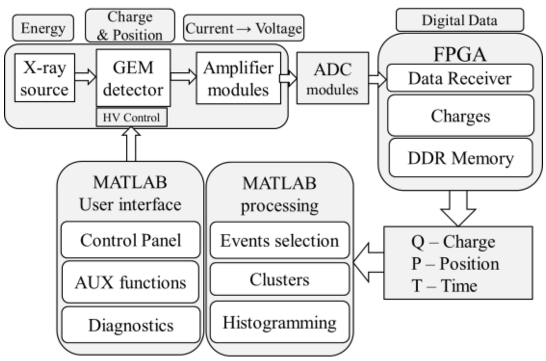

Fig. 2. Multi-channel measurement system scheme.

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3. Serial data acquisition

The serial data acquisition (SDAQ) is applied to obtain energy, spatial and time characteristics of SXR radiation [5]. All ADC samples exceeding the preset trigger level are acquired independently for each measurement channel. The ADC signal is analyzed within 40 sampling cycles (figure. 3 (a)). The first ten samples determine 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 match the time window. The last ten samples are used to check overlapping signals. The resulting serial data samples form a table of chronological triplets: [Q – charge value, P – channel number (position), T – triggered time]. Data packages are loaded sequentially to the DDR memory and finally are conveyed to the PC. The data structure is represented, then, by points in (Q, P, T) space corresponding to the signal samples. A typical constellation of the detected samples for Cu target activated by a single laser shot is displayed in figure. 3 (b), (c). The repetition of laser shots was 1 Hz. The plasma radiation emission from the target lasts ~40 clock cycles that matches with the time window of the presented ADC pulse.

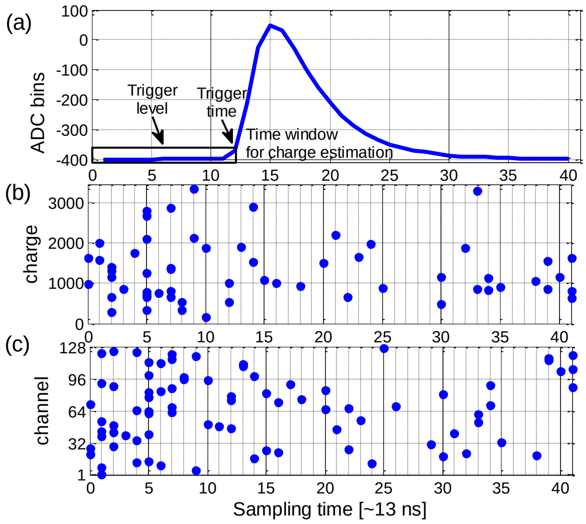

Fig. 3. (a) The ADC signal represented by 40 acquired samples. (b) The charge value distribution in time. (c) The charge position (channels) distribution in time.

4. Separation of coinciding pulses

Coinciding signals for high flux radiation cause the problem for cluster charge identification [6]. The period ~0.5 us of 40 cycles determines time resolution and limits the pulses frequency. Generally, series of many pulses can overlap mutually like in figure 4.

The general scheme of the signal conversion is presented in figure. 5. A hypothetical, original GEM detector pulse is the input for the amplifier and filter circuit of the electronics. The measured ADC discrete signal is the output of that circuit. It is assumed, that up to, so called, characteristic point, ADC signal depends strongly on the GEM detector pulse. But after the characteristic point it depends on the circuit parameters for a given initial condition. The statistical considerations relating to the signal shape and experimental investigations result in the reconstruction of the distorted ADC signal if the original GEM detector pulses are not coincided.

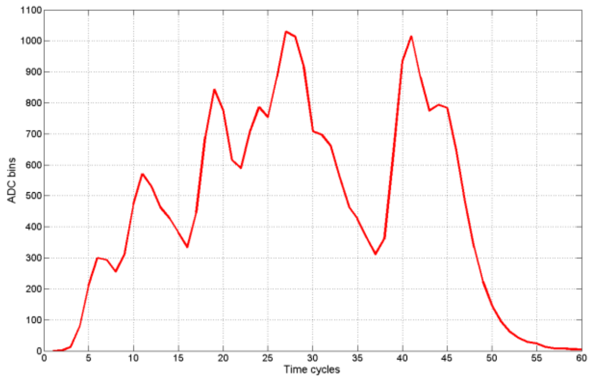

Fig. 4. Series of many mutually overlapping pulses.

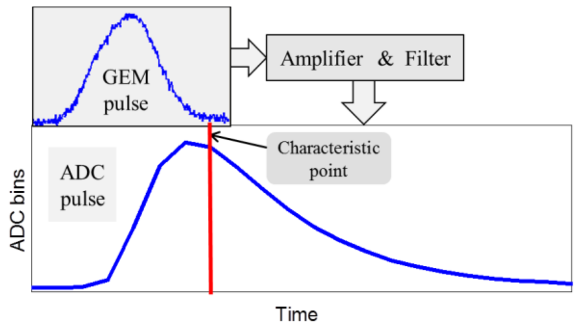

Fig. 5. GEM detector pulse as an input and ADC signal as the output of the amplifier and filter circuit.

5. Algorithm for hardware implementation

The digital arrangement carrying the separation of impulses out in the real time is presented in figure 6. It consists of blocs of synchronous registers *U2* and *U5* connected with asynchronous blocks: the subtraction unit *U1*, the characteristic point detector *U3*, the reference tail calibrator *U4* and the exit gate *U6*. The input signal S comes from the ADC module. The state of the *U2* register is represented with initial signal vector R(1:r+1), where r is an established number of samples for the growing phase of impulse to the characteristic point. The state of the second registers *U5* is represented with signal vector C(1:f-2), where f is an established number of samples for the decay phase of impulse (tail) after the characteristic point. The reference tail T(1: f) is stored in the memory.

The arithmetical and logical operations for the modules ***U1***: ***U6*** are stated as follow:

U1 – subtraction unit: u = S–c

U2 – first register: R(1:r+1)=R(2:r+2),   R(r+2) = u
for w=0, R(1:r)=0, R(r+1:r+2)=R(r+1:r+2)-F(1:2)

U3 – detector of characteristic point: local maximum or inflection point
if R(r-1) <= R(r) ∧ (R(r) > R(r+1) ==> w = R(r+1) elseif R(r)-R(r-1)>(R(r+1)-R(r)∧R(r+1)-R(r)<=R(r+2)-R(r+1) ==> w= R(r+1) else   w = 0

U4 – reference tail calibrator: F = w*T/T(1)

U5 – second register: C(1 : f-2) = [C(2 : f-2), 0] + F(3:f)

U6 – exit gate: P(1 : r+f) = [R(1 : r), F(1 : f)].

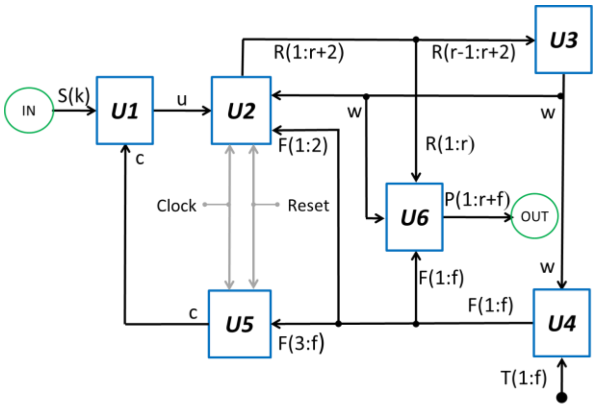

Fig. 6. Functional scheme of hardware implementation.

Many experimental simulations have been considered to verify separation of overlapped pulses. The pairs of regular signals was arbitrary selected from the measurement series for the simulation purpose. The selected pulses were superimposed with different mutual shifts. The efficiency of separation is reliable for the mutual displacement exceeding the certain threshold level. The pulses can be shifted several cycles only without clearly local minimum between them. The exemplary results of simulation are presented in figure 7, where the first pulse is bigger than the second one. Two superimposed pulses are shifted within the range 0 : 8 time cycles. The superposition of the pulses is considered for their reconstruction. Reconstructed pulses are compared to the original ones and relative errors for the charges estimation are displayed for two pulses respectively. For delay value greater than 3 time cycles algorithm efficiently separates pulses with reasonable errors. The greater delay the better separation is observed. The proposed algorithm can be apply iteratively for many superimposed pulses.

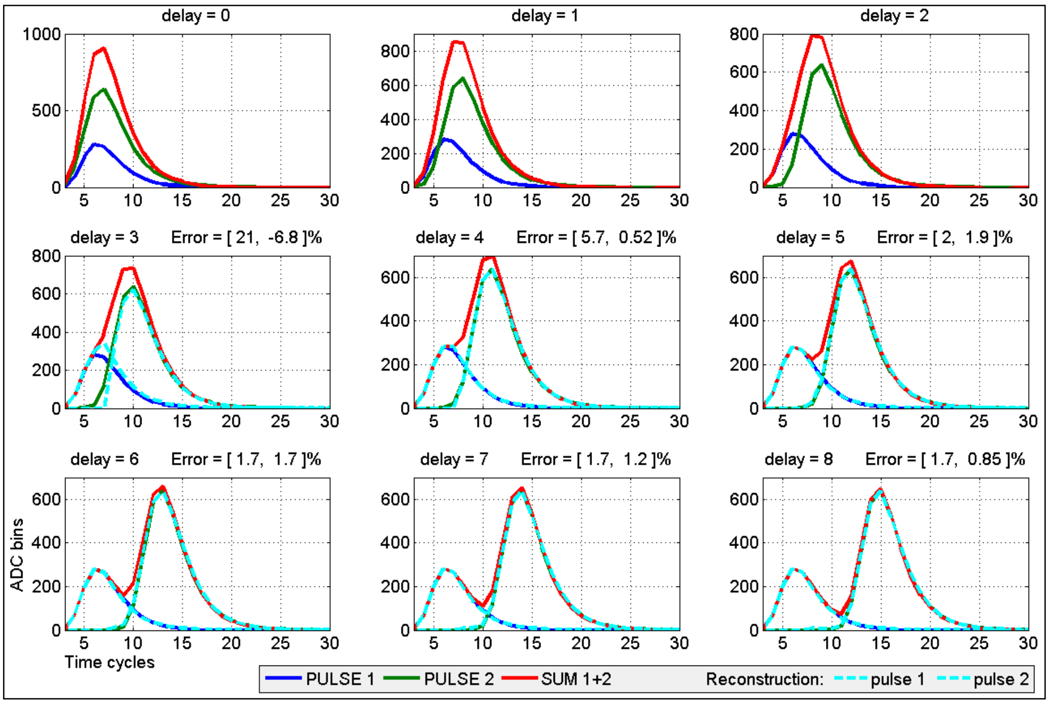

Fig. 7. Simulation results for two superimposed pulses for delay range = 0 : 8 time cycles.

The series of ten superimposed pulses by simulation is presented in figure 4. The original and reconstructed ten pulses are presented in figure 8.

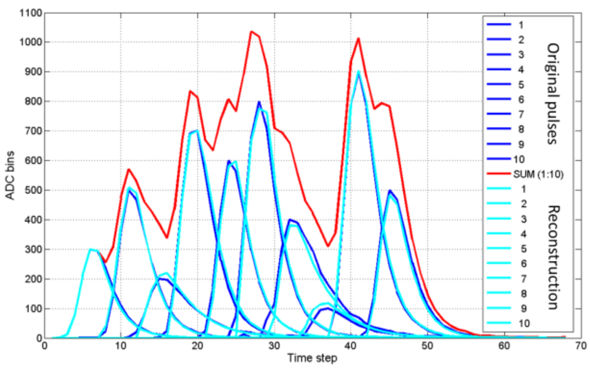

Fig. 8. Simulation results for two superimposed pulses for delay range = 0 : 8 time cycles

The series of real and unknown superimposed pulses is considered for the separation process. The individual separated five pulses presented in figure 8 were estimated sequentially.

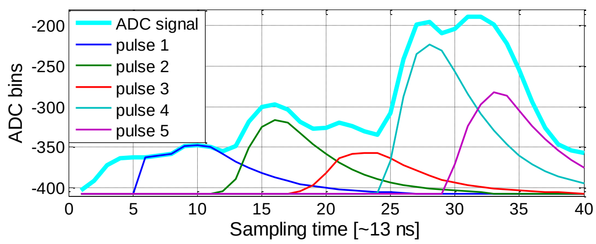

Fig. 9. ADC overlapped signal and five separated pulses

6. FPGA structure of the pulses separator

A distributed *firmware* for fast separation of pulses from the T-GEM detector was implemented in FPGA chip of Spartan-6 series placed on FMC board [10]. The new firmware, which is presented in the figure 10, replaced the previous one module described in [3]. Each 16-channels block processes the signals corresponding to the T-GEM 16 strips. Full compatibility for inputs and outputs signal has been retained.

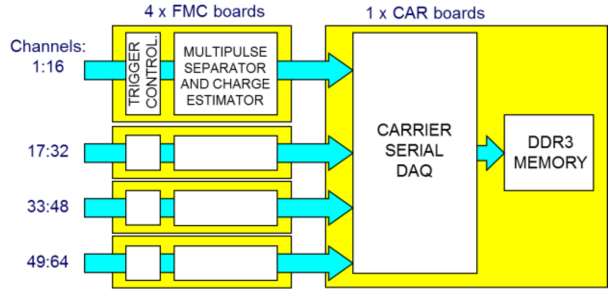

Fig. 10. Implementation of pulses separator blocks in T-GEM system.

The general scheme of the parameterized functional structure of the block called MULTIPULSE SEPARATOR AND CHARGE ESTIMATOR is shown in Figure 11. The pulses are split sequentially from superimposed input signals by means of separated LEVELx MULTIPULSE SEPARATOR cascading modules. Due to the above approach, pipeline modules are used and fast speed of data processing is achieved. Final charge values from the CHARGE ESTIMATOR modules are aligned in time in the LATENCY ALIGMENT modules respectively and then data are selected by the CHARGES MULTIPLEKSER output module".

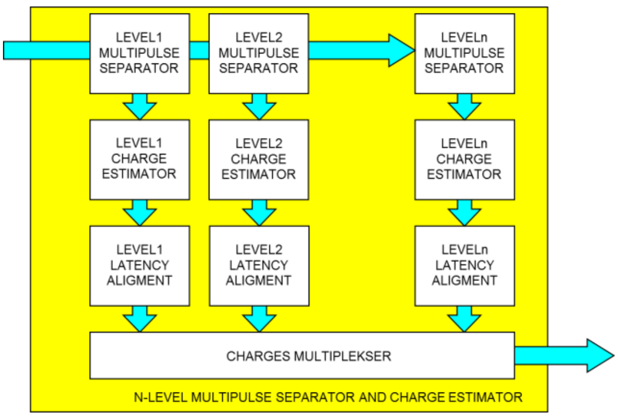

Fig. 11. The general scheme of the functional structure for the fast charges separation firmware.

The behavioral description technique for VHDL language enables to set several basic parameters, e.g.:

- N - number of separation levels (superimposed pulses),
- B - number of input data bits (amplitude probe resolution)
- L - length of pulse (time probe resolution)

7. Summary and conclusion

The multichannel measurement system based on GEM - Gas Electron Multiplier detector and essential data processing for X-ray energy and position recognition was presented. Serial data acquisition based on FPGA system performs fast processing for signal analyzing, charge calculation and memory operation. The new algorithm propose separation of overlapped signals caused by the relatively slow shaper. Separation of overlapped signals was successfully introduced and verified for simulation experiments. The proposed algorithm is efficient if the primary GEM detector pulses are not coincided. The expected time resolution improvement is ~50 ns comparing to ~500 ns previously. The algorithm is ready for the FPGA implementation with relatively simple arithmetic procedure. Typical histograms integrated in time for charge value distribution (scaled as the energy spectra) and cluster position are presented in figure 12 for a ^{55}Fe reference source.

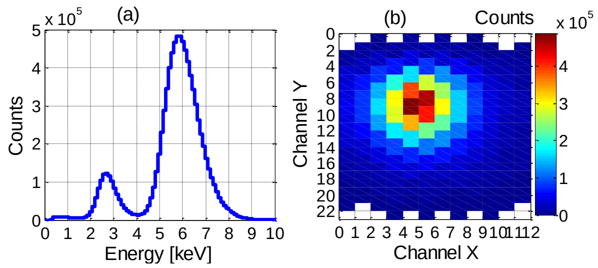

Fig. 12. The energy spectra for ^{55}Fe source and planar distribution for hexagonal array detector structure

Acknowledgments

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