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Multichannel measurement system for extended SXR plasma diagnostics based on novel radiation-hard electronics

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This work refers to the currently being developed extended soft X-Ray (SXR) plasma diagnostics system with the novel, radiation-hard generation of electronics. The paper describes the current status of the system development. The first goal was to compute SXR spectra – energetical and topological. It was done in the scope of designed hardware verification. Therefore, raw signal acquisition from GEM detector was implemented in FPGA. The system is based on the Gas Electron Multiplier (GEM) detector. The designed hardware is highly modular. One module of the system is capable of processing up to 64 analog input channels in real-time. Maximum number of supported channels is 2048 for extended version of the system. The system has two separate sections: the analog signal acquisition part, designed to be radiation-hard, and the signal processing part located in the rack. The system uses PCI-Express Generation 2 links with DDR3 memory for data storage and buffering. Xilinx Artix7 FPGAs mounted in the electronic modules perform currently signal acquisition functions. Acquired data is sent to the PC unit for postprocessing including cluster construction and spectrograms computation in the offline mode. Advanced low-level control software integration with signal processing application designed in Matlab was performed.

Keywords: GEM detector; soft X-ray plasma diagnostics; FPGA; data processing; soft X-ray measurement system

1. Introduction

The work presented in this paper refers to the currently being developed soft X-ray (SXR) plasma spectrography measurement system for use in the ITER-oriented tokamak. As the sensor unit, a GEM detector is used. It is equipped with a 128-channels, 1-dimensional readout. Since the detector part will be located directly in the WEST tokamak port,this part of the system must be designed as radiation-hard. The system is divided into two parts. The first one consists of analog front-end units with the GEM detector located in the tokamak port. The second part consisting of pre- and post- processing hardware modules, HV power supply, and protection system, is located in a rack situated a few meters from the tokamak's port [1-3].

The main goal of work is to perform plasma tomography using two GEM cameras: horizontal and vertical. Each unit will produce two kinds of spectra: SXR energy spectrum and SXR topological spectrum [4].

Due to expected intense plasma radiation (resulting in a high count of events registered by the GEM detector), it is necessary to provide a large number of channels handled by a fast data processing firmware.

Both hardware, firmware and different kinds of software (low and high level) was developed by the team, based on previous experience with the KX1 spectrographic system, installed at JET tokamak (Culham, UK) [5].

2. System hardware specification

The readout board of the GEM detector is connected to the Analog Front-End boards (AFEs), with the radiation-hard design. Each board handles transmission of 16 analog input channels. Boards are also equipped with transconductance amplifiers and onboard generators of calibration pulses for hardware verification purposes.

Each AFE board handles processing and transmission of 16 analog input channels. In 3-stage GEM foil detector, the signal has form of current in the range of hundreds of nanoampers. To enable further processing, high gain transconductance amplifiers are used. Unlike commonly used analog front end solutions, this stage simply converts current to voltage. The data processing algorithms provides estimation of charges in numerical form from directly acquired samples, so shaping and integration is not needed. Such approach requires DC-coupling in all processing chain, starting from detector signal up to ADC input. Due to high overall gain, multi-stage offset cancellation mechanism was applied. Each input channel on the ADC board has dedicated gain amplifier with gain and offset control which is used to compensate detector gain variations.

In order to meet the Nyquist requirements and provide sufficient timing resolution without sacrificing of the signal shape, second-order low-pass filtering was applied in such way that attenuation of 50dB is achieved at 65MHz. ADC sampling rate is 125MHz at ENOB of 8 bits. Preservation of signal shape is essential for advanced deconvolution algorithms used at further stage.

The digital section of the system located in the rack consists of Analog-Digital Converter boards (ADBs) connected to the backplane boards (presented in fig. 1).

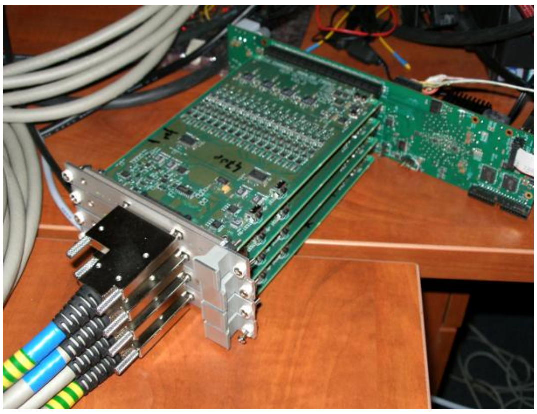

Fig.1.FPGA backplane board with installed 4 ADB boards – supporting 64 data processing channels.

Each ADB can work with up to 16 input channels using 75-125MHz sampling frequency. It is possible to perform offset calibration and modify the signal coupling. As the preprocessing unit, the Xilinx Artix7 FPGA is used, located on backplane boards. The communication with the PC is done through a PCI-E 8-to-1 switch using PCI-Express Gen2 interface. For data buffering purposes, the onboard DDR3 memory is used.

Complete system's hardware architecture layout is presented in figure 2. The figure shows the final system architecture with 128 input channels from the GEM detector.

More details about the developed hardware can be found in [6, 7].

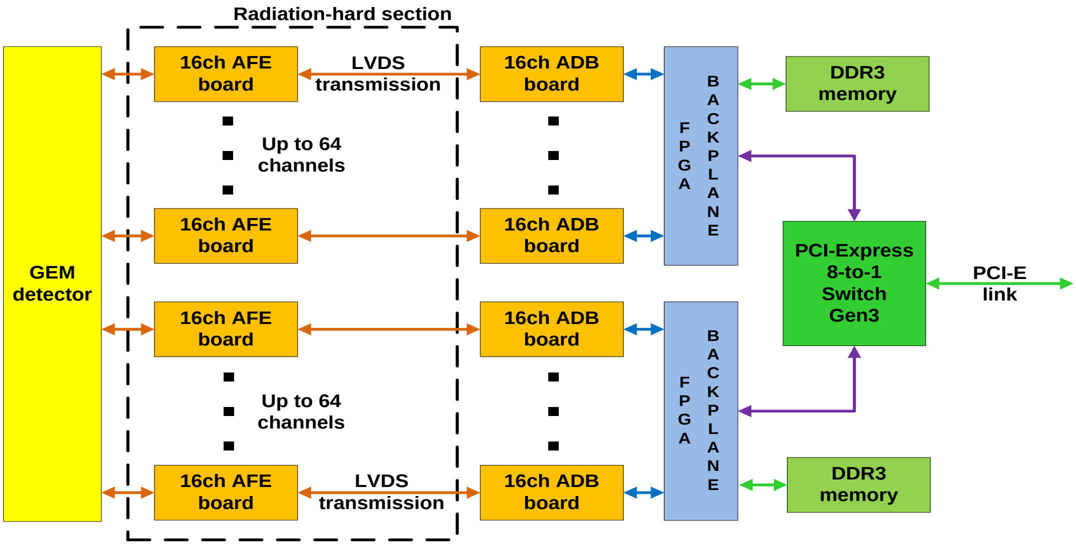

Fig.2.System hardware architecture – currently the system works with 64 input channels (one backplane board).

3. Firmware development

The implemented firmware in the FPGA on the backplane board performs key actions in data registration. Each FPGA can process up to 64 input channels from the GEM detector. The current sampling frequency is set to 75 MHz. The data is stored in the onboard DDR3 memory and send to the PC through the PCI-E Gen2 link for postprocessing (spectra computation). The HDL blocks are based on Wishbone and AXI interfaces, providing portable implementation for different kinds of measurement systems. The firmware allows to register up to 100k events per measurement from the GEM detector in form of raw, analogue signals from all 64 channels simultaneously.

Example of the extracted raw signals from the system's database is presented in fig. 3. The analogue pulses are correlated with one photon emitted by the X-ray source and registered by the GEM detector (electron cloud spreads over several GEM's readout channels).

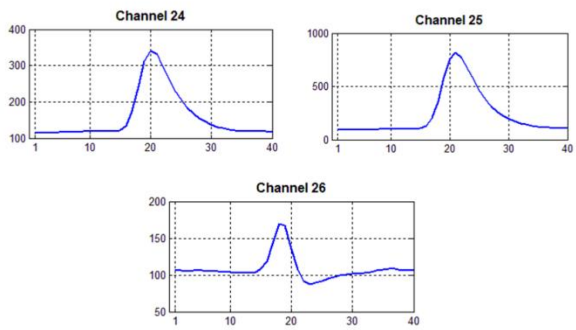

Fig.3.Example of raw signals registered by the FPGA firmware, corresponding to one photon registered by the GEM detector.

Thanks to recording of raw data, the Matlab-implemented postprocessing software has access to the whole information available in the digitized signal.

More details about the firmware development can be found in [8-10].

4. Control and postprocessing software integration

To perform data acquisition from the GEM detector and compute spectra: SXR energy spectrum and SXR topology spectrum, the system must be properly switched on, initialized and configured.

The appropriate initialization and configuration is ensured by the FCS - a modular framework for fast, advanced measurement systems. FCS uses on the drivers database for low-level communication interfaces, internal bus interfaces, and integrated circuits drivers. Its main function is to perform system initialization and configuration with automatic system self-check, diagnostics, and data management (downloading, parsing etc), providing an interface for user communication.

To perform spectra computation, advanced algorithms needs to be used, including cluster discrimination, charge computation and finally calculation of output products. To correctly register the charge signals from the GEM detector the system needs to be tuned by complex algorithms. Those compute correct offset level for all input channels, providing the best achievable dynamic range for the analogue input pulses. Those algorithms are implemented in the Matlab scripts. The Matlab software is a high-level data processing software available for the user. It can be installed on any PC. The connection to FCS is provided by the TCP/IP server[11], which is working on the mainframe PC. The FCS communicates with the system through PCI-Express and USB interfaces. Also, there is a separate server implemented for control of the high-voltage (HV) power supply unit, necessary for proper operation of the GEM detector.

The structure of the implemented software for multichannel measurement system is presented in fig. 4.

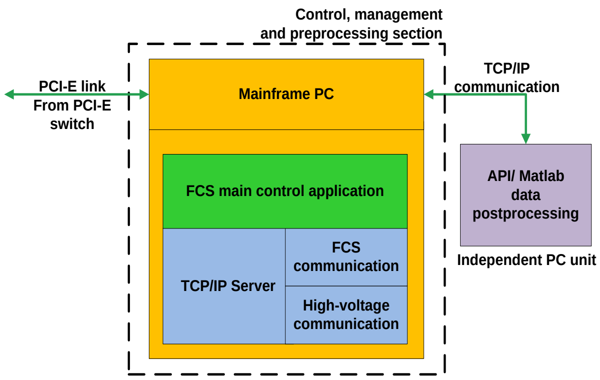

Fig.4.Structure of the implemented software containing applications running on the mainframe PC and external PC unit with Matlab postprocessing software connected via Ethernet.

The developed software (FCS and Matlab) is highly modular. Therefore, it is possible to further extend the system to support all 128 input channels. Also, it is possible to easily narrow the number input channels, and limit the system to 16 input channels without any need for software or firmware modifications.

More details about the developed software and postprocessing algorithms can be found in [12-15].

5. Performed laboratory experiments

After successful implementation and verification of developed firmware and software [10], first measurements were made.

The measurements were done using the 1-dimensional GEM detector with 64 output channels. Fe^{55} was used as an X-ray source, generating photons at the rate of approx. 1 kHz. With the source positioned at the center of the detector, first spectra were computed. For the test purposes, 10 000 events were registered by the system. The computed spectra are presented in fig. 5.

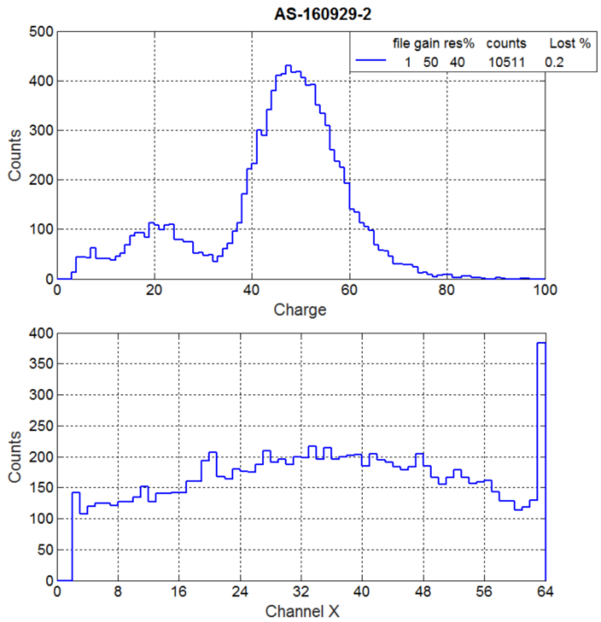

Fig.5.Energy and topology spectra of the registered Fe^{55} soft X-ray source with the 64-channels SXR measurement system.

The generated SXR topology spectrum confirms the correctly implemented algorithms and data processing paths: the X-ray source was positioned in the middle of the detector. On the corresponding plot, the most intensive radiation (counts) is registered in the middle channels, which confirms the correctness of the measurement. The peak on the 64-th channel is due to events that partially are outside the readout GEM detector readout board. Those events are assigned to the last channel.

The corresponding SXR energy spectrum also confirms the correctness of data acquisition and implementation of algorithms. On the plot there are two peaks visible: the first one corresponding to the Ar escape peak, and the second one to the measured X-ray source.

6. Conclusions

The designed firmware was successfully verified regarding the analog signal paths and data acquisition with 64 input channels.

The fast, multichannel preprocessing FPGA firmware with DDR3 memory and PCI-Express support was implemented and tested.

The FCS was used for the low-level system control and as a monitoring application. The advanced spectra computing tools implemented in Matlab were successfully integrated with the system. The first successful laboratory tests were performed with a 1D, 64 channels GEM detector and Fe^{55} X-ray source.

For the next steps it is planned to further develop the FPGA firmware parts related to the data processing – the data serialization and the algorithms for handling of frequent data bursts. It is also necessary to implement support for all 128 analog input channels, which will include handling of the second FPGA backplane board. The development of the FCS will be also continued regarding the automatic system diagnostics modes, handling of multiple FPGAs and fast data downloads. Tests in tokamak are planned to verify proper operation of the system in the real environment.

Acknowledgments

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