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Soft X-ray Diagnostic System Upgrades and Data Quality Monitoring Features for Tokamak Usage

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***Abstract*—The validation of the measurements quality after on-site diagnostic system installation is necessary in order to provide reliable data and output results. This topic is often neglected or not discussed in detail regarding measurement systems. In the paper recently installed system for soft X-ray measurements is described in introduction. The system is based on multichannel GEM detector and the data is collected and sent in special format to PC unit for further postprocessing. The unique feature of the system is the ability to compute final data based on raw data only. The raw data is selected upon algorithms by FPGA units. The FPGAs are connected to the analog front-end of the system and able to register all of the signals and collect the useful data. The interface used for data streaming is PCIe Gen2 x4 for each FPGA, therefore high throughput of the system is ensured. The paper then discusses the properties of the installation environment of the system and basic functionality mode. New features are described, both in theoretical and practical approach. New modes correspond to the data quality monitoring features implemented for the system, that provide extra information to the postprocessing stage and final algorithms. In the article is described also additional mode to perform hardware simulation of signals in a tokamak-like environment using FPGAs. The summary describes the implemented features of the data quality monitoring features and additional modes of the system.**

***Keywords*— data quality monitoring, FPGA, Verilog/VHDL, HDL, GEM detector, SXR plasma diagnostics, modular measurement system, data evaluation, tokamak**

I. INTRODUCTION

RECENTLY installed soft X-ray measurement system for plasma impurities monitoring was used during plasma campaign measurements in 2019 year [1]. At the moment, the vertical GEM camera is working, the most difficult one for the installation due to direct in-port detector placement [2]. The system consists of 103 Line-Of-Sights, thus allowing a large angle of tokamak vessel view, especially the divertor part.

This allows to perform studies about plasma impurities with large amount of diagnostic data. The key assumption of the measurement system is that due to modern FPGAs used (Xilinx Series7 at moment of design), the system allows to select valuable data (events related to photon emission from plasma) and then using streaming interfaces postprocess them in advanced Matlab algorithms [3]–[5]. On top of that, the system is capable of user-selected spectra generation, based on set parameters. In general – the scope of µs to ms. The system using internal hard drive is also capable of storing large amount of measurement data in form of raw signal. This is a unique capability, enabling multiple redo of algorithms to fit the best user parameters, have deep data analysis, and as well algorithms corrections based on the results and real data. As an output, high quality spectra data in scope of energy and topology can be produced. At the moment, the measurements were done without the He buffer in front on the GEM detector, resulting in decreased SXR intensity. However once the buffer will be filled, the intensity can raise even 10 times [6], [7]. Therefore, it is especially valuable to design various Data Quality Monitoring (DQM) tools implemented in FPGAs to provide detailed overview of system behaviour during measurements. The system is already working in global trigger mode [2] for GEM diagnostic stage. There are also ongoing laboratory tests of local/serialized triggering mode [8], [9], in order to achieve several times higher data compression. Despite of that, there are also aspects related to automatic system plasma registration, data storage, triggering, etc., that should be verified.

The DQM mechanisms allows, for example, to verify the signals quality, e.g. saturated, underflow signals automatic detection-rejection. Another useful, possible implementation would be to actively monitor the signals and for good quality waveforms (based on some assumptions) perform automatic charge computation. Such approach can reduce significantly data processing time, since FPGA can process values in scope of hundreds of nanoseconds. Another, different approach is to actively monitor the background components of the system, that are essential for proper data registration, triggering. One

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example would be to register and add to signal data extra values corresponding to firmware-specific data. Those could be channels offset levels, active triggers etc. Depending on the designed dataflow layout and implementation, this feature can however impact overall system performance.

In the following section the DQM modes implemented are described, both conceptual and implementation overview, as well new modes for easier functional system verification.

II. DATA QUALITY MONITORING FEATURES

The system is working in the difficult tokamak environment. Especially due to electro-magnetical interferences, neutron radiation and very low space for the electronics (cooling aspects). Therefore, it is especially valuable to implement data quality monitoring mechanism in order to better understand the measurements effects of the system and its data validity. Each of the FPGA boards is capable of handling up to 64 measurement channels from the GEM detector. The system is under verification in global trigger mode to observe the full behavior of the detector and measurement channels.

In this mode, the algorithms are sensitive to single photon registered by the detector and creates a snapshot of whole GEM detector, from all channels. All of the connected FPGAs are registering data at the same time. This mode gives extra data, that is not further used (called as empty channels, mostly with noise signal only, since only few channels are typically with charge). However, the system is designed in a way, to easily browse or analyze the signals offline, due registration capability of millions of events from all channels- both active or inactive (snapshot feature). Therefore extra information is given about offset fluctuations, signal or channels malfunctions on specific channels etc. This mode creates ability to:

- Verify the signals corresponding to events,
- Observe overall behavior of the GEM detector,
- Perform signal analysis in scope of:
    - Signal parameters distribution,
    - Noise level on each channel,
    - Influence of the valid signal on neighbor channels,
    - Etc.

However, some of the parameters or values are only available for FPGA without sending them to PC, making difficult, for example, to properly trace offset values.

The event registration is based on two factors:

- Trigger level for channel (charge level),
- Offset at specific channel.

Once the signal is above the offset and proper trigger level, system starts data registration. At that moment however, since this is a global trigger mode it is difficult to check:

- The triggering channel (or active triggers),
- Information from other FPGA about event registration (e.g. external triggers),
- Offset level (computed in FPGA) at the moment of signal registration.

Therefore, to have a full information about system quality on registration data, for example in scope of interferences, proper offset computations or signal fluctuations it is especially valuable to have extra additional information

- Active triggers for each event registration,
- Embedded dynamic offset level for events.

In the following subsections are described the conceptual assumptions made and the FPGA implementation details for extended event registration mode.

A. Local triggers DQM - Conceptual overview

In global acquisition triggering mode of FPGA firmware, the all-channel detector snapshot is created when signal on any channel is above the triggering level. The triggering level is set by user. The lower value corresponds to more sensitive measurements (especially low photon energy), however is also more fragile to the input noise. On opposite side, high value allows noise reduced measurements, however with much lower intensity and without low SXR energies. Since the system is working in tokamak environment, there are many sources of noises, especially from:

- Plasma phenomena,
- Magnetic fields (tokamak infrastructure),
- Other diagnostics units.
- Tokamak infrastructure (i.e. vacuum pumps etc.).

The noise level depending on the tokamak conditions can easily rise up, in form of pulse peaks, sine waves of low amplitude etc. This signal then can trigger the acquisition system if suddenly rise the offset level even for a short time. It can be omitted in software if this occurs only few times, however if such conditions repeat, the system can be easily saturated by incoming noise events, without any useful signal information from the GEM detector. The global triggering mode is especially sensitive for that, since even one noisy channel can fulfil the bandwidth with empty events. On top of that, the special link using LVDS standard is used for sending information (global trigger mode only) about trigger of data acquisition by side/external FPGA (to create global snapshot). It is valuable to have information about this signal upon event registration to know the proper source of data acquisition. In addition, the global tokamak acquisition trigger is also distributed among the system. The signal is used to inform the system that the plasma pulse has started. This additional information upon event registration is also valuable, to have confirmation that the acquisition start event is not suppressed temporary by some external interference signals.

B. Local triggers DQM - Implementation details

To implement the DQM capabilities of the measurement system, the global triggering mode was extended to provide information about the channels that had active triggers at the moment of event registration startup. The additional IPcore was design to keep the active triggers registered for each event (frame of 40 samples from each channels). The needed additional resources are very low, since only 64 1-bit registers are required with some simple control logic. Due to extended overall information data path, this mode is accurate up to 2-3 clock cycles for the current event. This is sufficient, since each event registration takes 40 clock cycles. In scope of DQM monitoring, in range of interest are mostly so-called fake-triggers. If the system is triggered in such configuration an empty event will be produced. Therefore, the spread of 2-3 cycles does not matter. The information attached to the event provides following information:

- Channels' trigger status – active/inactive (1 bit per channel);
- Side trigger status – when 2 FPGAs are working in global trigger mode, FPGAs need to exchange information between to indicate that one of the units started data acquisition. Therefore, it can be checked, if the viewed event was started by the local FPGA or externally triggered (for example to check for noises on external lines);
- Measurement enable trigger – global on/off triggering signal regarding plasma measurements. Provide information if during event registration this signal was active (for all measurements should be set to 1).

The data structure for each event, despite raw data fields, consists of one 1024bit (due to bus width 64 channels x 16bits) header row. The header layout:

- Synchronization pattern 128bits,
- Timestamp 64 bits,
- Reserved fields 64 bits.

This layout is then multiplied 4 times (256bx4) to achieve full bus width (resulting from 64 ADC channels and 16-bit sample values from each one). There is no need at the moment to embed more information to the data frame.

This layout fits perfectly to implement local trigger DQM mode in "Reserved" fields and removing part of synchronization pattern. The synchronization pattern is mostly for software tests and therefore it can also partially be considered as part of reserved field.

Since there are no added new bits, the global triggering mode performance stays completely unaffected. The total data throughput is in range of 240-250 kevents per second, which is a very good result for a diagnostic mode. Each of the FPGA creates data pack of 64 channels and send it to PC.

The data is transmitted without any change to the measurement PC for further postprocessing in Matlab software. More details about data handling in scope of DQM mode can be found in [10].

This mode is also very valuable for further postprocessing algorithms, especially is scope of the charge computation. If working in global trigger mode, the postprocessing algorithm needs first check every frame in scope of signal above the triggering level. After, on selected signals is possible to perform charge computations. In addition, in one frame can occur multiple pulses, corresponding to several clusters at one time. Therefore, it is necessary to check each channel for localization of valid signals. Having triggering channels information attached to beginning of every event reduces the necessity of each channel verification resulting in faster computation speed. However, it should be indicated, that this mode provides information about the channels that started the event registration. If some pulses came few clock cycles after, they will not be registered in local triggers fields.

C. Dynamic offsets DQM - Conceptual overview

The triggering system is a bit more complex. The hardware of the system is based on analog front-end boards [11], [12]. It consists several signal forming stages, especially shaping, amplifying and offset correction units. Each channel has independent input offset level. Those levels are tuned by the algorithm from the PC, however a few bins of difference (in range of 1024) are still persistent among channels. In addition, during measurements the system AFE boards heats-up in rage of 50-70 ºC, depending on the cooling system performance and type. This can also influence the change over time of the analog offset value. The user provides mostly the charge trigger value (relative value). In such configuration the offset must be computed in real-time by the FPGA value to trace any changes of the signal level over time. If the tracing algorithm is too sensitive or too slow, it will result either in trigger suppression or more sensitive trigger.

Due to mentioned behavior, the offset value need to be:

- Initially set-up to one common value,
- The offset value needs to be dynamically observed during the measurement,
- Corrections to the trigger level should be done in real time – only possible using FPGAs.

It is difficult to provide one triggering value common for every channel. For the current implementation user provides the relative trigger value, comparted to event pulse (charge) without including offset value. The FPGA firmware have implemented the dynamic, real-time offset computation unit for each channel. After the initial offsets settings, the IPcore computes every few ms new offset value based on mean signal value.

During the event registration, the offset computation subsystem is disabled. It is necessary, since the added pulse value (distributed over several samples) will influence the mean offset value. The effect of influence depends on signal intensity – the higher the more improper offset computation will be. For DQM reasons it is valuable to implement mode that allows to registr the computed real-time offset level in-FPGA for each event. This can give important information about:

- Offset fluctuations over time for dynamic offset mode,
- Behavior of the algorithm under high photon flux.

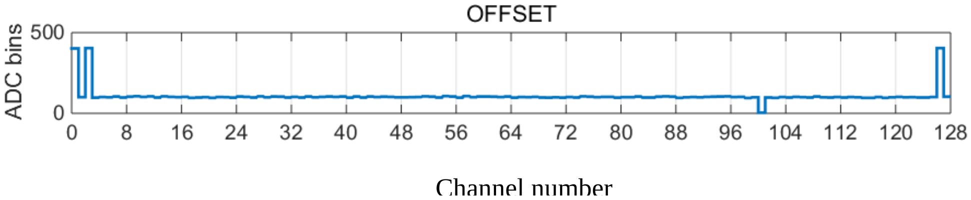

Fig. 1 Reference offset values after typical initialization procedure over analog channels. Side channels on plot are user-configured to higher offset values for DQM feature mode validation.

D. Dynamic offsets DQM - Implementation details

The FPGA implementation registers the offset value for each independent channel. This crate a matrix of 64 x 16-bit values with dynamically computed offsets. After startup of event registration in the FPGA, the dynamic offsets values are latched and attached as one row to the end of the data frame. The values are attached to each event. Under Matlab tools during postprocessing it is possible to do a verification of this offset computation mode, as well offset behavior, especially by creating plots of:

- Offset value with added relative trigger
- Comparison with Local Trigger DQM mode and offset values
- Comparison of difference between dynamic offset DQM values and offset from first sample of the event (assuming that the pulse is in the middle of the frame)

This mode creates extra 1024bit data for each event. The basic global triggering mode provides 799 events per each DMA packet (4MB). With added DQM, the number of events is reduced to 780 events – resulting in ~97% performance capabilities of previous mode. Assuming more less linear approximation, the performance of this mode is ~240kevent/s. Therefore, the global trigger mode with all DQM additional components stays at very similar performance.

During laboratory measurements and plasma measurements this DQM mode can give valuable information regarding input channels behavior and system data quality.

In addition, attaching the offset values to the events reduces multiple times the CPU computations of the spectra, since the stage of offset computation from raw data in the event can be easily skipped. In order to properly compute the charge value, it is necessary to first remove any offset value. If this data is not provided by the FPGA, it is necessary to run first the algorithm in CPU to compute offset and after to compute the charge. Since this can be done for each channel individually, having such information will reduce multiple times the computation time.

There were also performed first validation tests on the measurement system. The reference values are shown on Fig. 1. Three channels were set to have much higher offsets values than the others, in order to easier verify the DQM component.

The plot in Fig. 2 shows 24 following events registered with trigger 0, corresponding to fast noise acquisition (tests purposes). The data have been successfully validated, for example in term of the raised 3 channels. As shown after few events, the dynamic offset level has increased over 20 bins. This gives a good reference, how the trigger level can behave over time. To have better understanding of this effect, raw data should be checked, that are registered with the shown dynamic offsets. This is also valuable information about offset computations during plasma pulse, since the algorithm is blocked during voltage pulses. The user can compare the expected trigger level with computed offset.

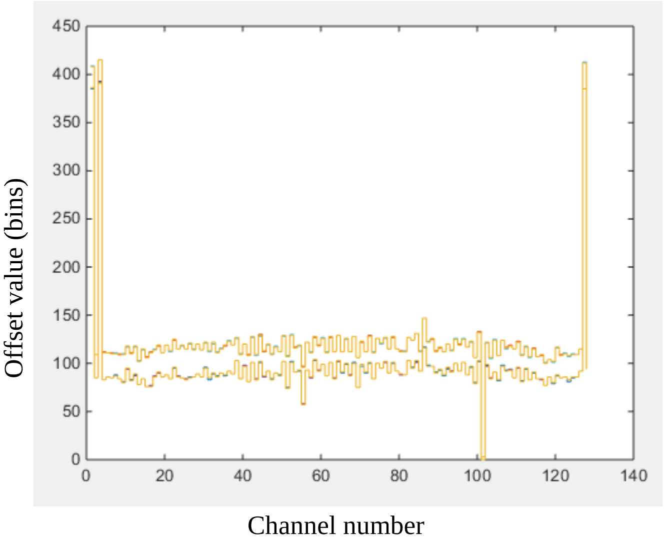

Fig. 2 Computed dynamical offsets in FPGA. Data acquired using dynamic offsets DQM feature implemented in new firmware. Edge channels manually set to higher values for verfication proper signal interpretation

This mode is planned to be upgraded to have automatic plotting regarding offset level from initialization with relative trigger value using offset level from the DQM. Then it can be shown, on which level the pulse was really registered. This mode is valuable to be connected with local trigger DQM mode in order to check, it the proper channel is triggering the event.

More details about data integration with the Matlab and embedded PC platform on data postprocessing level can be found in [10].

III. ADDITIONAL TESTING FEATURES

In order to fully verify the measurement system, not only it measurement capabilities, but also the functional features, all the time there should be access to the tokamak and its infrastructure. It is impossible, therefore for some functionality, additional testing features should be implemented in the system. One of them is an automatic, autonomous data registration system. It is rather an easy task, if the system is only focused on following scheme:

Trigger plasma start → data registration → trigger plasma stop → data describing and storing

However, for the GEM detectors is valuable also to register reference spectra, since the parameters can vary a bit due to temperature, pressure or humidity fluctuations.

For reference spectra is used the ^{55}Fe isotope source, mounted in front of the GEM detector. The extended measurement scheme is as follows (Fig. 3).

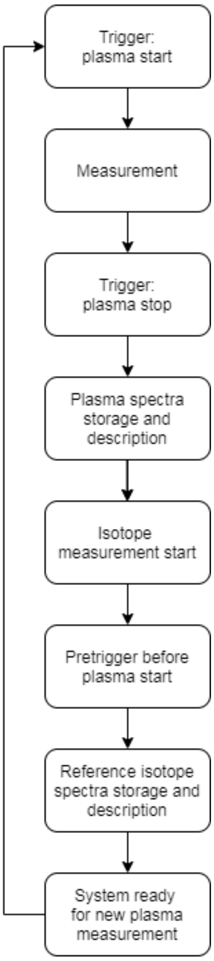

Fig. 3 Measurement scheme with reference isotope soft X-ray spectra

In order to make this schematic automatic is necessary to use two triggers:

- Plasma start trigger,
- Pretrigger ~ 1-2minutes before plasma.

Having those 2 triggers is possible to register plasma, after storage register the isotope spectra and then wait for another plasma experiment. This automatization involves and extension on the system on all of the levels of algorithms:

- FPGA firmware,
- Low-level control software,
- Data registration software,
- Matlab routines.

In Fig.4 is presented a layout of hardware triggering signals with correlation to plasma. The trigger 1 is providing information regarding very precise start of the acquisition. However, with use of GEM detectors, some calibration/ reference measurements should be done with the ^{55}Fe sources during idle time. For that reason, second trigger is planned to be involved. Having it configured as a pretrigger, it is possible to measure isotope during idle time, and reinitiate the system just before plasma (2 minutes should be well above the requirements). Second advantage of having long reference measurement is that much larger number of events will be registered.

To support the triggers in such layout, the PCIe Switch firmware was modified and better handling of 2 independent signals is now provided. Especially the IPcore handling the triggering section was upgraded to have simulation mode.

Since various elements need to be tested, it is necessary to have a source of the triggers. Due to limited access to the tokamak, some laboratory solution had to be done. For simple trigger it is easy to use just a signal generator, however with more complex scenarios it is better to implement some more advanced to have a field of tests of the full components integration.

Therefore, the triggering section has now capability to generate simulation signals. From the system side, those signals are handled as real signals. Modification of the FCS software and adding new set of registers allow a configuration of this mode in scope of:

- Enable simulation mode,
- Configure timing in seconds of:
    - Plasma time,
    - Pretrigger time,
    - Idle time.

The simulation works continuously, thus giving possibility to test the system as it would be working on tokamak hall during whole measurement day. The design has been also integrated with data management software and Matlab, described in [10].

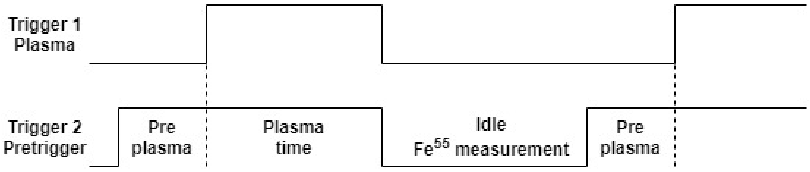

Fig. 4 Triggering system including 2 external hardware triggers: plasma trigger and pretrigger

IV. SUMMARY

In the paper are described an upgrades for a new measurement system for plasma measurements. It uses a multichannel GEM detector with more than 100 channels. It consists an analog stage and FPGA for data preprocessing and streaming. With use of FPGA it is possible to provide unique feature of postprocessing data based on raw signals, selected by the FPGA. Whole spectra, i.e. topological, energetical with user-selectable time resolution are produced by high-end embedded server at postprocessing stage. This approach is different then the one used at JET tokamak [13], [14], where all of the data were computed in the FPGAs. The main difference is that implementation of complex algorithms, e.g. pile-up resolution, clustering, etc. is difficult in FPGAs, especially where multiple channels need to be considered. In the current approach Matlab or C algorithms are working on raw data, allowing high flexibility in modifications of the algorithms, and also its validation.

The multichannel GEM-FPGA SXR measurement system was working on WEST tokamak during 2019 plasma campaign. The first results shows good correlation with other diagnostics, as described in [1]. Due to preparation for more automatic functionality of the system as well integration with the WEST tokamak database, new modes have been developed. Main topics of improvements involved:

- Automatization of the measurement mode related to plasma,
- Added new mode of second trigger for reference spectra measurements,
- Simulation mode for external triggers embedded in the FPGA hardware.

In order to provide high quality measurement data, the FPGA firmware was also upgraded to provide extra information regarding the measurements:

- Triggers that activated the event registration in global trigger mode including external trigger and acquisition trigger,
- Dynamic offset value computed in FPGA for corresponding event.

That information is added to every event in the data frame. The performance of the design is kept almost at the same level. The implementation has been successfully validated on noise data acquisition. The laboratory tests are planned for full validation of the design. It is planned that Matlab software will be upgraded to provide more diagnostics mode related to the available data from new firmware. At the next stage, upon system verification of the new modes it is planned to implement data serialization algorithms resulting in fast data streaming based on registration of single channels that had active trigger. In this mode, the DQM local trigger part will not be necessary, however offset level DQM feature is planned to also be implemented in fast data registration mode.

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