

# Measurement Capabilities Upgrade of GEM Soft X-ray Measurement System for Hot Plasma Diagnostics

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**Abstract**—The paper presents improvements of the developed system for hot plasma radiation measurement in the soft X-ray range based on a Gas Electron Multiplier (GEM) detector. Scope of work consists of a new solution for handling hardware time-synchronization with tokamak systems needed for better synchronization with other diagnostics and measurement quality. The paper describes the support of new modes of triggering on PC-side. There are communication and data path overview in the system. The new API is described, which provide separate channels for data and control and is more robust than the earlier solution. Work concentrates on stability and usability improvements of the implemented device providing better usage for end-user.

**Keywords**—Measurement system, GEM, DAQ

## I. INTRODUCTION

MEASUREMENT systems used in hot plasma diagnostics are often complex and specialistic. Researchers of different professions use them, so they have to be as simple to use as possible. Such a system should be autonomous and user-friendly due to the high number of measurements per day. Direct access to the machine after installation on the experiment site is often limited, so it has to be robust and easy to check in case of failure or unknown issues.

The presented measurement system uses a Gas Electron Multiplier (GEM) detector and is constructed for the detection of soft X-ray (0.1–20 keV) radiation. It is build to monitor radiation generated by hot plasma impurities in tokamaks [1]. Our group have prepared whole solution from scratch [2] - from GEM detectors [3], hardware and firmware [4], [5], control software [5], real-time platform [6] to algorithms [7]. In the system, calculations are divided between hardware (FPGA) and CPU based processing. It is the second generation of the system based earlier only on FPGA calculations used at JET tokamak. Advantages to other similar systems used in hot plasma diagnostics are:

- 1) raw-data acquisition for measurement quality

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- 2) FPGA usage for fast adjustments of triggering and data acquisition
- 3) CPU side algorithms - much more cost and time-efficient than FPGA side implementation

The detector is working in a difficult environment. Measurement results prepared on altered signals can lead to significant errors. Some of the major problems addressed are overflow, underflow and pile-up effect of the signal. To prevent this additional data quality monitoring solution is implemented [5]. Current trends in similar measurement systems do not provide raw signal/data download but concentrate on statistics like Time over Trigger (ToT) [8], which do not address this issue as precisely as our solution. Incorrect signals or complex pile-ups will be calculated as valid single pulses distorting measurement output. Example, difficult to interpret signal, is presented in figure 1.

To fully track the system state during measurements, the device requires multi-level diagnostics, action, and state logging.

Measuring properties of a dynamic process like hot-plasma requires e.g. at least microsecond synchronization with other devices (best if done by hardware signal - more stable and repetitive than software-based one). It can be needed to compare and verify measurements from many different diagnostics and measurement systems. It is useful to fully understand the evolution of the phenomena and to prepare complete conclusions based on different approaches to the research.

If data will be processed in real-time, the measurement system can provide useful data to be used by other parts of the tokamak in a feedback loop.

## II. IMPLEMENTED IMPROVEMENTS

To fulfill the requirements stated in the introduction, our system has gone a few important upgrades, described below, ranging from FPGA triggering mode changes, improvement of measurement metadata, synchronization with external devices, offline and online mode, API and stability improvement.

### A. Triggering modes

Previous iterations included global triggering mode [9]. It works by saving measurement data from all channels at once as soon as one or more signals rise above the trigger level on



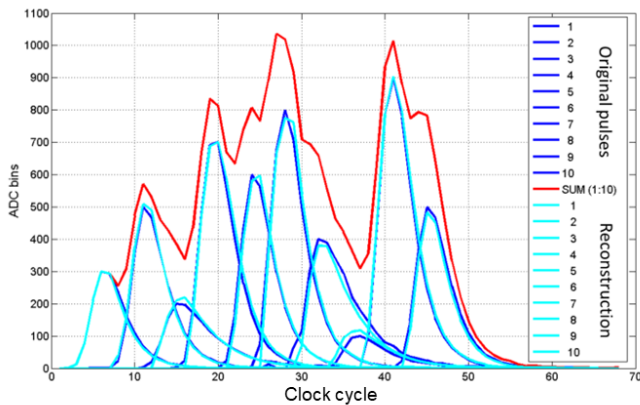


Fig. 1: Exemplary difficult pile-up signal presenting outcome of prepared signal reconstruction algorithm [10].

any of the channels available. This mode is useful for validation of the system and crosstalk investigations. Algorithms for different spectra generation based on raw data X-ray pulses were implemented in MATLAB as reference [10] and in low latency versions [7] on CPU and GPU devices. This solution was comprehensively tested in terms of hardware performance [9] and whole data path throughput and latency with CPU algorithms. Tests have proven bottlenecks:

- data layout in memory - not optimal for CPU calculations, preventing zero-copy solution (needed double buffering), additional data preparation needed
- data from all channels is send - not all channels provide valuable X-ray related data

Despite described inefficiencies system can process data with latency less than 10ms (more details in [11]).

Another version - local triggering mode is implemented [12]. It solves the above issues by proper memory layout for CPU calculations and not sending irrelevant data for hot plasma measurements. In simplification, data is sent from the measurement channel only if the signal rises above the trigger level on that channel. It provides much lower bandwidth utilization during the low intensity of radiation. It is during verification and tests.

Comparison of local and global triggering modes are presented in figure 2 showing major differences.

However, this version provided difficulties in real-time CPU algorithm preparation and upgrade. There is a new version of triggering mode being prepared named Zero-Suppression [13]. This mode merge improvements of local triggering mode with ease of computation part based on the global triggering mode. It provides a lowered need for bandwidth as in local trigger mode with the correct layout in memory. Additionally, it provides measurement frames synchronization between channels, so the CPU side does not have to measure triggering time differences as in local triggering mode.

In the current state of the system, all of triggering modes are available to change by CeSI interface (see section II-E2).

## B. Data quality monitoring

To improve diagnostics value of measurements, an additional set of metadata on the FPGA side (like register values) are send to the PC side. Processing such information was implemented in software improving possibilities of on-site noise and crosstalk identification. More about the implemented solution can be found in [14].

## C. System synchronization and plasma cycle

During the hot plasma generation campaign, there are many plasma generation shots during a single day. To maximize research output our measurement system can do diagnostics (like radiation measurement of reference  $^{55}\text{Fe}$ ) as long as possible minimizing time needed to prepare for another shot. This solution requires two triggers. One for ongoing plasma, second for an indication of constant time before next shot (summary presented in fig. 3).

Our earlier solution provided only hardware trigger related to plasma pulse. Without lacking pre-plasma signal (e.g. 30 seconds before next shot) it was impossible to implement diagnostics part optimally.

Solution with two triggers in the measurement cycle can be divided into three different parts:

- 1) diagnostics - calibration and inter-measurement preparations, other technical tasks e.g. data download to PC
- 2) preparation - preparation for plasma measurement
- 3) plasma measurement - main measurement in the sequence

Switching between parts can be done by hardware signals, software communication, timeout or number of registered pulses. A whole single sequence is presented in figure 3.

Hardware part provides nanosecond accuracy for starting measurement and synchronization with the execution of a plasma pulse.

In the current state of the system, we provide internal and independent hardware-based trigger generation, which can be used for simulation and tests [14]. We implemented handling a whole described cycle on the PC software side.

It is possible to change  $t_1$  signal on figure 3 from hardware to software-based one without losing much of its advantages. However  $t_2$  should be hardware base due to needed stability and accuracy.

## D. Measurement architecture

The system is capable of online and offline processing, which differs by functionality.

Data flow path, with other available software modules are presented in figure 4. Low-level control is done by FCS (reading FPGA state, measurement state change etc.), where measurement control (internal procedure for measurement) and data download (daemon running in the background) is handled by Dispatcher and it's submodules.

1) *Online mode:* Online processing is done in whole in terms of the measurement unit. It requires real-time algorithms, which can process raw data fast enough to not degrade spectra output. If the computation will be too slow system

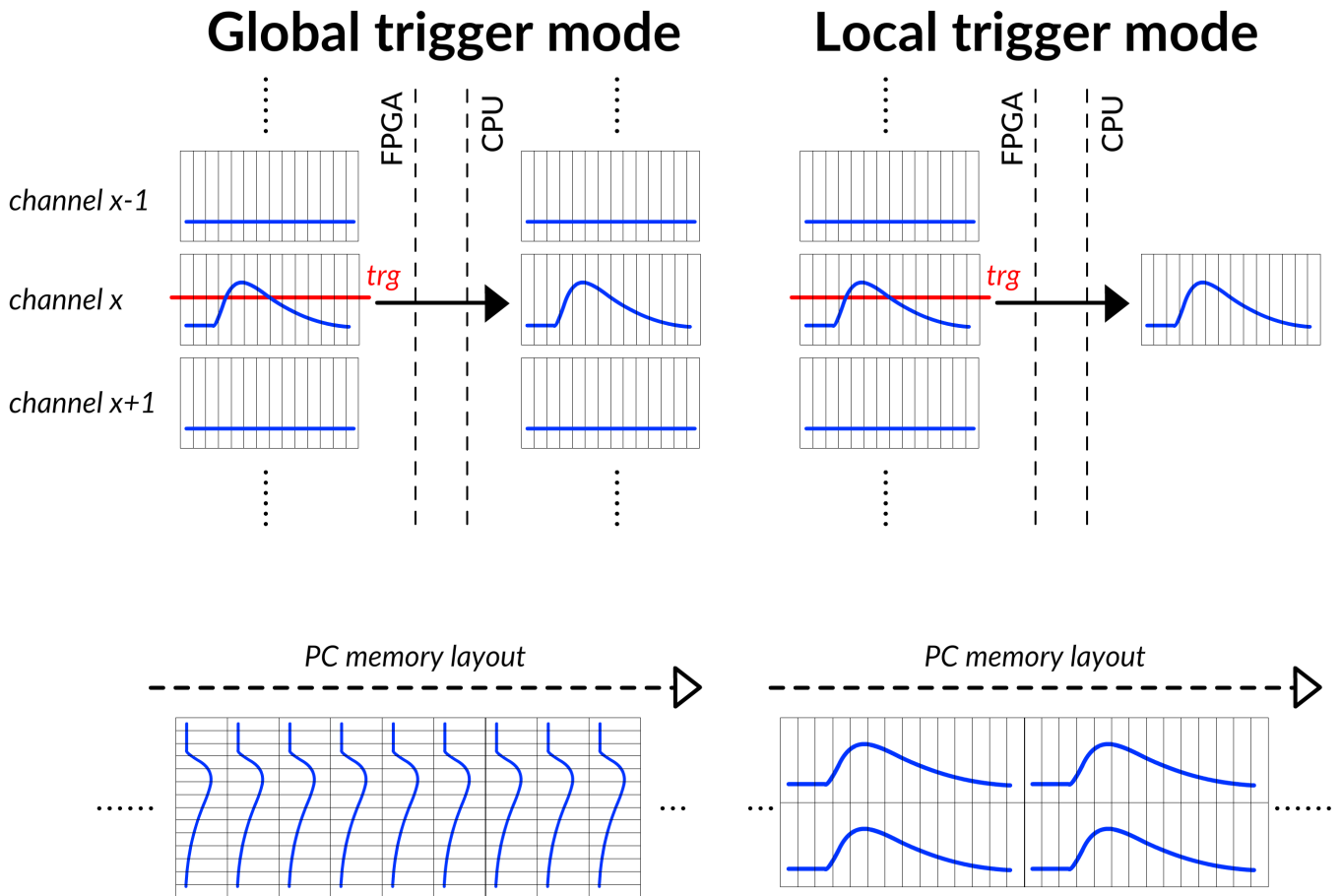


Fig. 2: Comparison of global and local triggering mode. Upper part show difference that only data from channels with pulse-related signals are sent to the PC side in the local trigger mode. The bottom part presents the simplified memory layout of signal data with proper alignment for CPU processing.

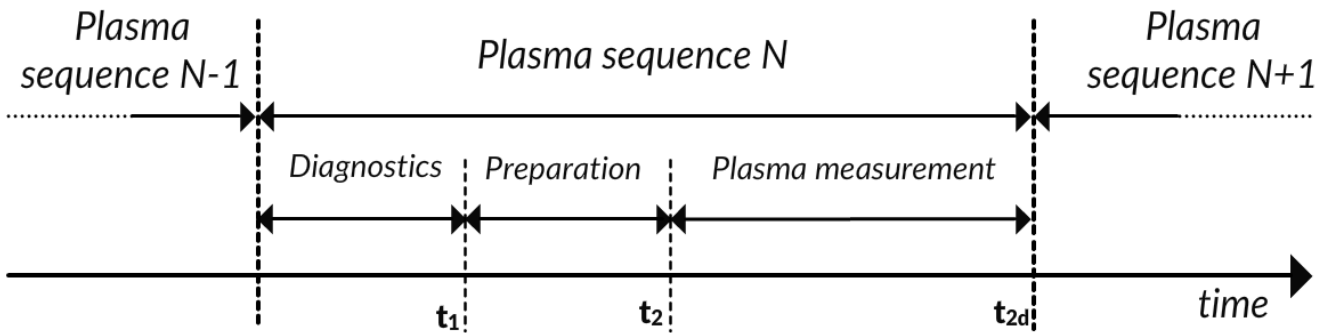


Fig. 3: X-ray plasma radiation measurement cycle with highlighted different hardware triggers and states of the system between them.  $t_1$  is a moment when pretrigger signal rises up,  $t_2$  when plasma trigger rises up and  $t_{2d}$  is a moment, when  $t_2$  lowers down.

can temporarily, at some point, reject data packets (early architecture of the solution is presented in more details in [6]).

10 ms latency of data computation in global triggering mode was achieved and available throughputs were tested and presented in [11]. Similar tests are pending for other triggering

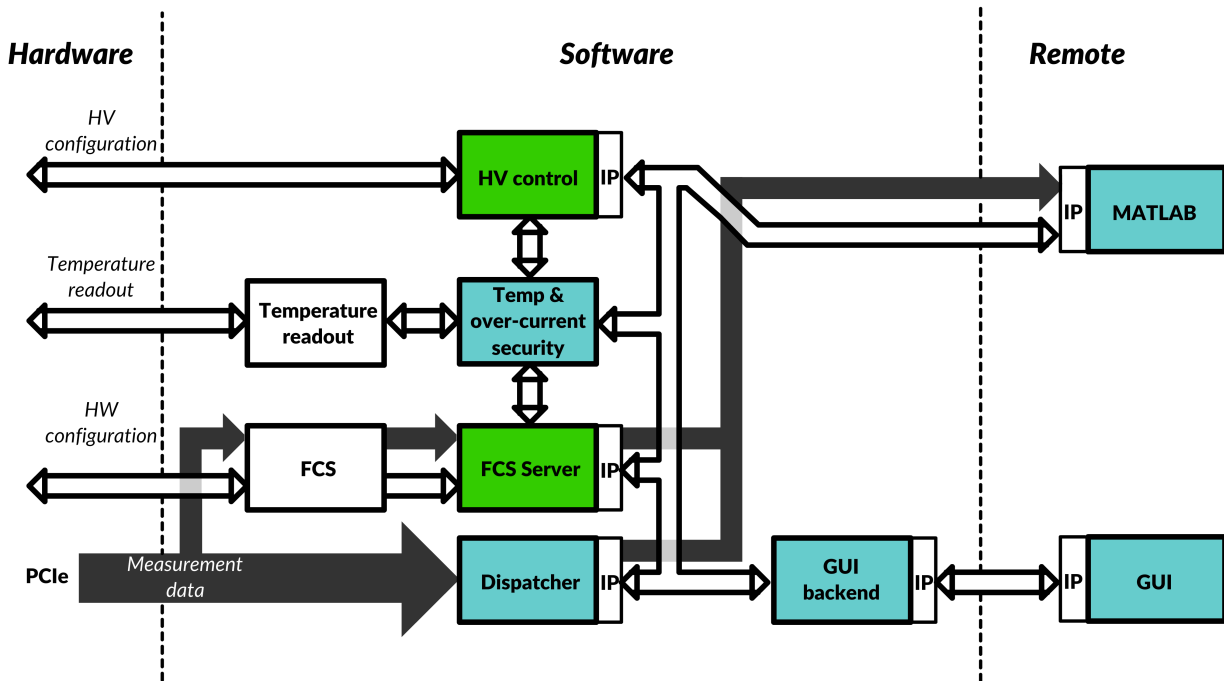


Fig. 4: Dataflow architecture of the presented system. White arrows describe control path flow, grey one measurement data path. Example client presented in the picture is written in MATLAB but not limited to this environment.

modes, where lower latency and bigger throughput (in terms of significant data) on the same bandwidth should be achieved.

2) *Offline mode*: Offline mode provides API for processing raw-data out of the scope of the measurement unit. Raw data have to be downloaded from the system to PC with large archiving capabilities due to the significant size of single measurement files (up to 2.38 GB per each second of plasma measurement).

Raw-data can be discarded or downloaded depending on the needs of the measurement. Currently, the system can store around 13.45 seconds of continuous raw data measurement in memory with 32 GB of RAM designated for measurements (calculations based on system capability tests [9]). Amount of archived unprocessed data can be improved by adding additional memory or mass storage with enough fast interfaces able to handle demanding bandwidth.

This mode is useful for diagnostics of anomalies, noise and interferences occurring in difficult environments like hot plasma measurement. Raw data can be thoroughly analysed by any specialists with any software capable of reading binary data.

a) *Sequential API*: This API is implementing a polling pattern in state machine-like requests. Configuration, measurements and data download are done sequentially. User cannot start new measurement before data is downloaded. This API was implemented mostly for test purposes and to be used by simpler clients in laboratory-like configuration, with stable Ethernet connection without time restrictions between measurements.

b) *State-less API*: In multi-diagnostic experiments, there is a possibility of sharing an Ethernet network with other

diagnostics. Downloading offline data during measurements should be avoided not to put unnecessary load on the network. Moreover, measurement should be independent of data download - multi-gigabyte stream can take too long to download in some configurations significantly limiting the number of possible measurements during a single day.

This API was created to improve error-handling, handle real world scenarios and autonomous externally controlled measurements better than sequential API.

There are two concurrent communication channels:

- 1) control channel - is used to control and start the measurement,
- 2) data channel - to send on-the-fly compressed measurement data and metadata.

Exemplary client for data channel was implemented in Python 3 to be used as a script on GNU/Linux based systems and compiled to the executable file for Windows operating systems.

Exemplary client for control channel was implemented in MATLAB for our team to prepare and easy tweak measurement parameters and easy diagnostic with verification codes. It can be used during plasma measurements by the tokamak state machine and it is divided into two sections:

*Measurement script*: It should be called any time before  $t_1$  time (see fig. 3). Parameters are hidden from the end-user/tokamak state machine and can be tweaked by our team during the installation. During its execution measurement is prepared. The system is waiting for plasma shot, executes measurement and begins diagnostics stage (fig. 3). It returns with message and status code as soon as the next  $t_1$  signal



(a) *CeSI* example with the used system. There are available modules for control, firmware, *Tailon*, data channel of State-less API and other.

(b) *Tailon* subsystem showing reading from temperature sensors.

Fig. 5: *CeSI* and *Tailon* WWW services used in the current state of the system.

is detected. The script should be called as soon as possible as it returns for the system to be ready before the next  $t_2$  signal arrives. There is no data download directly related to the execution of this script.

*Spectra generator*: This script consumes data downloaded from the data channel (concurrently e.g. by exemplary .exe Python 3 client). As soon as data is available it can be executed. It converts binary data, executes processing algorithms. Generated spectra are stored in files, which can be easily sent to other subsystems in comma-separated values (CSV) format or other if needed.

Basic measurement routine consist of using first communication channel with ID parameter describing measurement (e.g. plasma shot number). Data is downloaded in format:

$$[trg\ mode] - [date] - [ID\ parameter] - [time] - 1 \quad (1)$$

Where date is in format YYMMDD and time HHMMSS. For example with ID *EXAMPLE* measured on October 2nd, 2020 at 14:26:52 data downloaded by second channel will stored in directory *AS-201002-EXAMPLE-142652-1*.

The proposed solution is easy to implement in external devices e.g. used for autonomous measurements like tokamak control software. The directory will store binary files with saved measurement raw data and metadata files corresponding to this exact measurement. From this point, end-user can perform computations and analysis. The directory name is compatible with reference algorithm implementations in MATLAB.

### E. Stability and usability improvements

Much of the prepared work was done to improve overall robustness and end-user experience of our system.

1) *Stability*: Our system provides a constant measurement of temperatures in important parts of the electronics. High Voltage module work is supervised, communication errors are detected and sensors readout is provided. (see fig. 4).

The system logs corresponding information to the log subsystem and perform described actions.

2) *Usability*: Gaining insight over past tests and experiences some of the controls were prepared to be used by end-user. Much of them were earlier available only for specialists or required their supervision.

All of the available software modules [15] can be controlled by WWW service. *Supervisor* [16] and *CeSI* [17] were used as implemented user friendly solution. It provides the possibility of the easy restart, start and stop of services and ensures that services work continuously in case of critical errors.

For log files access from different modules of the system *Tailon* [18] software was implemented. User can choose logfile from the list to show last recorded events, check temperatures of the system and its state. (see fig. 5b).

*CeSI* and *Tailon* implemented in the system is presented in figure 5.

Logging was improved. More information is logged and it is easier to recreate events in case of errors. With the usage of *Tailon* [18] (see fig. 5b) user can download the log and send to the specialist in order to investigate what and when a problem occurs in case of hard to analyse errors.

*Logrotate* utility was enabled and used for limited storage space used for diagnostic files.

## III. CONCLUSION

The universalism of the presented solution was improved. The system can perform measurements with three basic measurement triggering modes. Global is the best one for data validation and crosstalk check. It was recently upgraded with data quality monitoring solutions. Local and zero-suppression modes are designed to work with target measurements. They are implemented and during validation, latency and throughput tests with data storage only (offline mode) and in online mode (along with algorithm updates). System measurement synchronization with plasma shots was improved, now providing two

hardware triggers - one for the preparation stage, the second one for the time of measurement. State-less API for concurrent measurement control and measurement data download was tested and is used as the main way of communication with the system. Much work was put into improving the working stability of the presented device. The system is now much more user friendly with available WWW services easy to handle by non-specialist users.

#### IV. FUTURE WORKS

With new triggering modes available, there is need to fully test throughput and latency of computing platform/data path with data download only and with algorithms in online mode as done in earlier work for global triggering mode [9], [11]. Currently access to control modules and log files are available in different WWW services. Measurement and data download are done by standalone executables/scripts. System will benefit from WWW GUI client aggregating all information in one place. Moreover such solution could work without additional software and thus be more versatile and universal solution.

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#### REFERENCES

- [1] D. Mazon, M. Chernyshova, G. Jiolat, T. Czarski, P. Malard, E. Kowalska-Strzeciwiłk, S. Jablonski, W. Figacz, R. Zagorski, M. Kubkowska, G. Kasproicz, K. Pozniak, W. Zabolotny, S. Larroque, J.-M. Verger, M. O'Mullane, J. Mlynar, A. Byszuk, and A. Wojenski, "Design of soft-x-ray tomographic system in west using gem detectors," *Fusion Engineering and Design*, vol. 96-97, pp. 856 – 860, 2015, proceedings of the 28th Symposium On Fusion Technology (SOFT-28). [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0920379615002215>
- [2] W. M. Zabolotny, G. Kasproicz, K. Pozniak, M. Chernyshova, T. Czarski, M. Gaska, P. Kolasinski, R. Krawczyk, P. Linczuk, and A. Wojenski, "Fpga and embedded systems based fast data acquisition and processing for gem detectors," *Journal of Fusion Energy*, vol. 38, no. 3, pp. 480–489, Aug 2019.
- [3] M. Chernyshova, T. Czarski, K. Malinowski, E. Kowalska-Strzeciwiłk, J. Krol, K. T. Poźniak, G. Kasproicz, W. Zabolotny, A. Wojenski, R. D. Krawczyk, P. Kolasinski, I. N. Demchenko, and Y. Melikhov, "Development of gem detector for tokamak srx tomography system: Preliminary laboratory tests," *Fusion Engineering and Design*, vol. 123, pp. 877 – 881, 2017, proceedings of the 29th Symposium on Fusion Technology (SOFT-29) Prague, Czech Republic, September 5-9, 2016. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0920379617303307>
- [4] G. Kasproicz, W. M. Zabolotny, K. Pozniak, M. Chernyshova, T. Czarski, M. Gaska, P. Kolasinski, R. Krawczyk, P. Linczuk, and A. Wojenski, "Multichannel data acquisition system for gem detectors," *Journal of Fusion Energy*, vol. 38, no. 3, pp. 467–479, Aug 2019.
- [5] A. Wojenski, K. Pozniak, D. Mazon, and M. Chernyshova, "FPGA-based novel real-time evaluation and data quality monitoring system for tokamak high-performance GEM soft x-ray diagnostic," *Journal of Instrumentation*, vol. 13, no. 12, pp. P12.024–P12.024, dec 2018.
- [6] P. Linczuk, R. D. Krawczyk, W. M. Zabolotny, A. Wojenski, K. T. Pozniak, M. Chernyshova, T. Czarski, M. Gaska, G. Kasproicz, E. Kowalska-Strzeciwiłk, and K. Malinowski, "Data distribution and dispatching software for processing measurement data acquired with SXR GEM-based system," in *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018*, R. S. Romaniuk and M. Linczuk, Eds., vol. 10808, International Society for Optics and Photonics. SPIE, 2018, pp. 1219 – 1224.
- [7] R. D. Krawczyk, T. Czarski, P. Linczuk, A. Wojenski, P. Kolasinski, M. Gaska, M. Chernyshova, D. Mazon, A. Jardin, P. Malard, K. Pozniak, G. Kasproicz, W. Zabolotny, E. Kowalska-Strzeciwiłk, and K. Malinowski, "The software-defined fast post-processing for gem soft x-ray diagnostics in the tungsten environment in steady-state tokamak thermal fusion reactor," *Review of Scientific Instruments*, vol. 89, no. 6, p. 063504, 2018. [Online]. Available: <https://doi.org/10.1063/1.5022131>
- [8] M. Garcia-Sciveres and N. Wermes, "A review of advances in pixel detectors for experiments with high rate and radiation," *Reports on Progress in Physics*, vol. 81, no. 6, p. 066101, may 2018. [Online]. Available: <https://doi.org/10.1088/2F1361-6633/2Faab064>
- [9] P. Linczuk, R. Krawczyk, A. Wojenski, W. Zabolotny, K. Pozniak, M. Chernyshova, T. Czarski, P. Kolasinski, G. Kasproicz, M. Gaska, E. Kowalska-Strzeciwiłk, and K. Malinowski, "Performance Evaluation of Developed GEM-based X-ray Diagnostic System," *Acta Physica Polonica B Proceedings Supplement*, vol. 11, p. 637, 01 2018.
- [10] T. Czarski, M. Chernyshova, K. Malinowski, K. Pozniak, G. Kasproicz, P. Kolasinski, R. Krawczyk, A. Wojenski, P. Linczuk, W. Zabolotny, A. Jardin, D. Mazon, K. Jakubowska, G. Boutoux, F. Burgy, S. Hulin, and D. Batani, "Measuring issues in the GEM detector system for fusion plasma imaging," *Journal of Instrumentation*, vol. 13, no. 08, pp. C08.001–C08.001, aug 2018. [Online]. Available: <https://doi.org/10.1088/2F1748-0221/2F13/2F08/2Fc08001>
- [11] P. Linczuk, R. Krawczyk, A. Wojenski, W. Zabolotny, M. Chernyshova, K. Pozniak, T. Czarski, M. Gaska, G. Kasproicz, P. Kolasinski, E. Kowalska-Strzeciwiłk, and K. Malinowski, "Latency and throughput of online processing in soft x-ray GEM-based measurement system," *Journal of Instrumentation*, vol. 14, no. 05, pp. C05.001–C05.001, may 2019. [Online]. Available: <https://doi.org/10.1088/2F1748-0221/2F14/2F05/2Fc05001>
- [12] P. Kolasinski, K. T. Pozniak, T. Czarski, M. Linczuk, A. Byszuk, M. Chernyshova, B. Juszczak, G. Kasproicz, A. Wojenski, W. Zabolotny, P. Zienkiewicz, D. Mazon, P. Malard, A. Herrmann, and D. Vezinet, "Serial data acquisition for GEM-2D detector," in *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2014*, R. S. Romaniuk, Ed., vol. 9290, International Society for Optics and Photonics. SPIE, 2014, pp. 723 – 730. [Online]. Available: <https://doi.org/10.1117/12.2075911>
- [13] P. Kolasinski, K. Pozniak, A. Wojenski, P. Linczuk, R. Krawczyk, W. Zabolotny, G. Kasproicz, M. Chernyshova, and T. Czarski, "Zero-Suppression Trigger Mode for GEM detector measurement system", *International Journal of Electronics and Telecommunications*, This volume.
- [14] A. Wojenski, P. Linczuk, P. Kolasinski, M. Chernyshova, D. Mazon, G. Kasproicz, K. T. Pozniak, M. Gaska, T. Czarski, R. Krawczyk "High-performance soft X-ray diagnostic systems' data quality monitoring features for WEST tokamak", *International Journal of Electronics and Telecommunications*, This volume.
- [15] A. Wojenski, P. Linczuk, R. Krawczyk, P. Kolasinski, M. Gaska, K. T. Pozniak, G. Kasproicz, M. Chernyshova, T. Czarski, E. Kowalska-Strzeciwiłk, and K. Malinowski, "Communication model for multi-level control, management, and acquisition firmware-software implementations for tokamak plasma diagnostics systems," in *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2019*, R. S. Romaniuk and M. Linczuk, Eds., vol. 11176, International Society for Optics and Photonics. SPIE, 2019, pp. 1285 – 1288. [Online]. Available: <https://doi.org/10.1117/12.2536890>
- [16] *Supervisor: A Process Control System.*, (accessed 10 November 2020). [Online]. Available: <http://supervisor.org/>
- [17] Gamegos, *CeSI (Centralized Supervisor Interface) GitHub page.*, (accessed 10 November 2020). [Online]. Available: <https://github.com/gamegos/cesi>
- [18] *Tailon - application for looking at and searching through log files.*, (accessed 10 November 2020). [Online]. Available: <https://tailon.readthedocs.io/en/latest/>