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The stand-alone optimized post-processing software platform for hot tokamak plasma diagnostics

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ABSTRACT: This article concerns novel software solutions that were introduced in the framework of development of a fast real-time computation system for soft X-ray diagnostics in the tokamak WEST (Tungsten Environment in Steady-state Tokamak) in CEA, Cadarache, France. The objective of study was to provide a fast processing of data at high throughput and with low latencies for investigation of interplay between particle transport and Magneto Hydro Dynamic (MHD) activity. The results can in future contribute to implementing a fast response feedback for the reactor control mechanisms. The long-term objective is to develop new methods to sustain the fusion reaction in the tokamak. In the implemented electronic system, a stand-alone software computation engine was designed to handle data collected at high rates in the server back-end. Signals are obtained from the front-end FPGA mezzanine cards that acquire and perform a selection from the GEM (Gaseous Electron Multiplier) detector. The implementation allowed for benchmarking and evaluation and optimization of plasma processing algorithms, resulting in authorial fast library for plasma diagnostics was written in C++. New algorithms originate from reference offline MATLAB implementations. They were redesigned in order to conduct runtime analysis during the experiment in a novel online mode of operation. The present achievements in algorithms optimization and performance results are discussed. Back-end software and hardware architecture is presented with available data evaluation tools. New mechanisms that allowed deployment of online computations at WEST tokamak are shown. The Data Quality Monitoring has been introduced to assure the coherency with reference computation in MATLAB.

KEYWORDS: plasma diagnostics; GEM detector; data processing; acquisition system; optimization

Contents

1. Introduction

In the framework of providing mechanisms of maintaining thermal fusion reaction, various advanced diagnostics and control systems are intensively developed. The complexity of this phenomenon is extreme from both physical and engineering perspective [1][2]. Vast comprehensive research is undertaken to construct the ITER (International Thermonuclear Experimental Reactor) – the first tokamak to produce more energy than to consume [3]. The primary objective of presented study it to provide fast methods of soft X-ray hot plasma plasma diagnostics for the WEST reactor, in which numerous solutions for future use in the ITER are evaluated.

The requirement for GEM detector based soft X-ray acquisition systems has been widely stated. The main purpose for the WEST is to implement in future mechanism of calculating the spatial distribution of radiation [4,5], dependent from plasma content. The device should allow to conduct a tomographic reconstruction [6,7] in order to investigate the tungsten transport phenomenon during the experiment. This may contribute in future to an increase of reaction efficiency and the provision of safe mode of operation, for occurrence of tungsten from a tokamak plasma-facing walls hinders the fusion and, when accumulated in plasma, can damage the reactor. In figure 1 the two detectors configuration in tokamak is depicted for measurements.

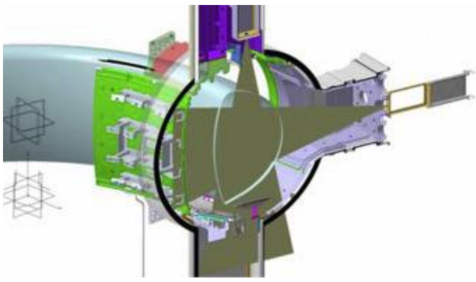

Fig. 1. The dual-detector configuration in WEST Cadarache for tomographic radiation reconstruction [6].

2. GEM detector based diagnostic system

The comprehensive acquisition and diagnostic electronic system was developed for the deployment in WEST. Its previous implementations have proven themselves reliable in the JET (Joint European Torus) tokamak in Culham, UK [8,9]. With requirements and constraints stated by CEA, new version was implemented, with novel architectural, hardware and software solutions. The device for WEST tokamak exhibits several unique features. The data are acquired at high rates - for each of up to 128 channels of the detector the signals are sampled at up to 125 MHz. With 16-bit ADCs, up to 30 Gigabytes per second is fed to the system. The data rate is subsequently reduced during system runtime. This is conducted in the FPGA front-end mezzanine cards and, subsequently, in the server back-end. The FPGA selection mechanism lessens the throughput to an extent that the data could be sent to a server by a PCIe 2.0 x 4 interconnect. Approximately 2,5 Gigabyte per second is the maximal output of the front-end. In the server back-end processing, histograms are generated, either of which incorporating two-dimensional spatial (channel number) and spectral (impulse charge) distribution. Results can be downloaded and evaluated in MATLAB or sent to control systems. The output at this stage is maximally 1 Gigabyte per second for generation of 10000 histograms (one every 0.1 ms), each with dimensions of 128 (channels size) and 100 (impulse charge range). Considering maximal output rate, the throughput reduction ratio is 32. Two modes of operation are provided, each with particular real-time constraints:

- **The offline analysis.** In such, the data are collected and analyzed after the experiment. This does not differ from the previous revisions of the system except for higher. For this reason, the SSD drive in the system is quickly saturated should it be fed directly with FPGA front-end data. Therefore, in the server back-end, the further reduction is conducted by calculating histograms. After the experiment, they can be downloaded and visualized in MATLAB. The for this mode constraints amount to processing the data in the server back-end at the same throughput as they are fed by the FPGAs.
- **The online analysis.** In such, the histograms are generated and sent to the control systems during runtime. This mode is under evaluation. The lowest possible, several-millisecond latency between data collection and histogram generation is pursued. This is designated to provide in future new methods of controlling the tokamak's plasma content with a feedback signal from the diagnostics.

The architecture of the electronic system to meet these requirements is depicted in figure 2.

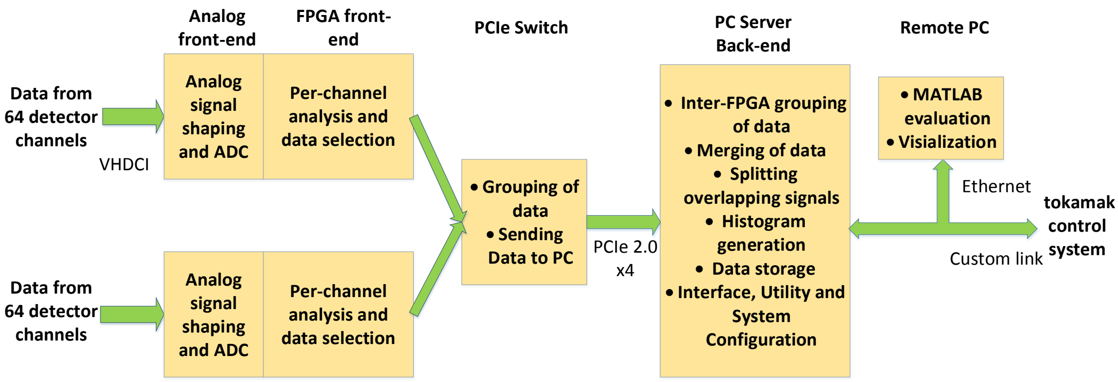

Fig. 2.. The processing pipeline architecture.

The device is a result of comprehensive studies and numerous authorial implementations concerning the custom power supply and cooling [10], novel GEM detector design [6,7,11], analog signal shaping [12], providing custom FPGA mezzanine cards with firmware (utility, selection algorithms)[12,13], data transmission (fast front-end to back-end protocols, fast methods of FPGA-to-PC transmission)[14-16] and algorithmic development, from both plasma physics (metrological issues, interpretation of signals)[17-19] and computer engineering perspective (parallel optimized algorithm design, hardware-oriented optimization, scalability study on the back-end server) [20-25].

The architecture has been justified and confronted with its contemporaries in [26]. The system's evaluation copy for laboratory tests is presented in figure 3 with its major modules.

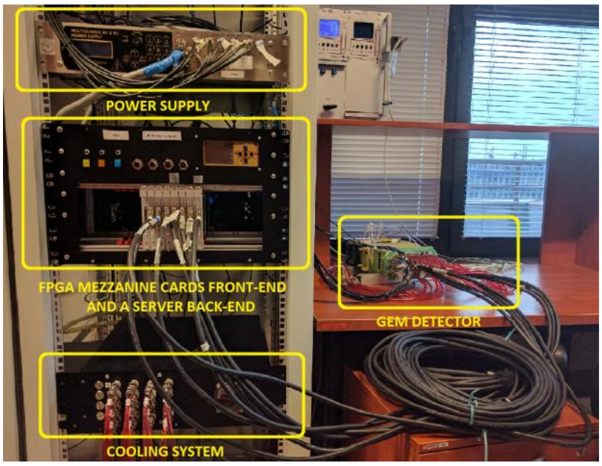

Fig. 3. The full system evaluation configuration and a depiction on its most important components.

Regarding the server back-end, the computations are conducted with redesigned and highly optimized algorithms, analyzed and evaluated in [17-25]. In the subsequent chapter it is presented how the plasma offline MATLAB diagnostics has been adapted in the framework of a stand-alone software computation engine, providing requested modes of operation.

3. Back-end and a software computation engine

Apart from communicating, interfacing and utility functions, the following computations are conducted in a server:

- grouping of signals from different boards,
- splitting overlapping signals and identifying impulses with calculating their charges (designed in an offline variant in [17]),
- recognition of clusters (that is, groups of pulses in spatial and temporal vicinity) -offline MATLAB versions have been shown in [18,19] and optimized in C++ as MATLAB-callable functions in [20-22],
- calculating histograms for detected clusters.

Initial optimization was conducted in [20-22] along with a preliminary evaluation of various software and hardware approaches, presented in [23-25]. These results led to a development of a stand-alone computation software engine written in C++. The platform supports both requested modes of operation. In order to adapt the offline algorithms to an online processing, following issues needed to be overcome:

- The whole-data-set post-experimental analysis had to be replaced with incremental analysis of an upcoming packets.
- Adequate output data format had to be established. One needed to enable calculating a 3-D histogram of spatial (channel number), spectral (charge value) and temporal

(analyzed time quantum) distribution. Results should both be able to be analyzed after the experiment or to be sent throughout the running experiment.

- The time dimension index had to be redefined. In offline analysis analyzed time interval was set after the experiment (where the duration of experiment was known). This has been replaced with a time resolution parameter set before the experiment (allowing to analyze data for an unknown duration). This allowed to generate new histogram and to send it to the remote PC or a tokamak control system every time quantum defined by time resolution while the experiment was running.

The mechanism of continuous data processing that fulfilled such requirements is presented in figure 3.

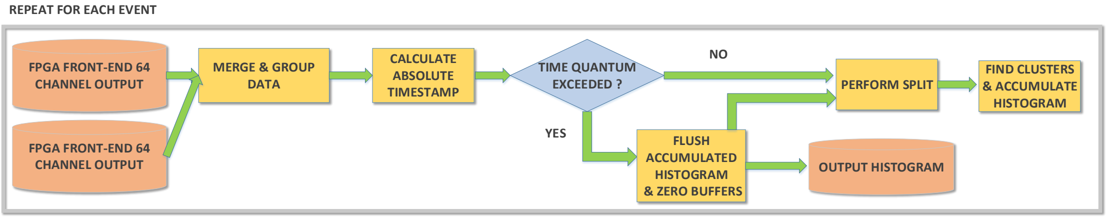

Fig. 3. The continuous data processing mode of operation. Data buffers are marked in red, operations are marked in yellow. Decision making for histogram generation is marked in blue

The packages from FPGA front-end of up to 4 MB are continuously fed to server in either mode of operation. At first, data grouping and per-event analysis occur. Event is a selected chunk of data from the front-end – a 10-Kilobyte collection of 40 samples from each of 128 channels with a timestamp. It is checked if the timestamp fits within a current range defined by the time resolution. If it exceeds the range, the presently-accumulated histogram is flushed and a new one is accumulated, initially set to zeros. If the event fits within the range then no flush occurs. At the end of the measurement, last histogram is flushed as well. For every interval defined by time resolution a two-dimensional histogram of spectral and spatial distribution is generated. Their collection allows to construct a three-dimensional histogram with additional time dimension equaling the duration of the experiment as defined by counted time resolution quanta. Such an approach allows both analysis after experiment as well as on-the-go computations with incrementally upcoming results.

Another issue was providing evaluation tool for a stand-alone algorithms library. Since the reference MATLAB offline algorithms proved themselves reliable under laboratory conditions, one needed to compare them with a redesigned set of optimized algorithms, to prove compliance or to assess the extent of changes in the results. A Data Quality Monitoring Mechanism was developed as depicted in figure 4.

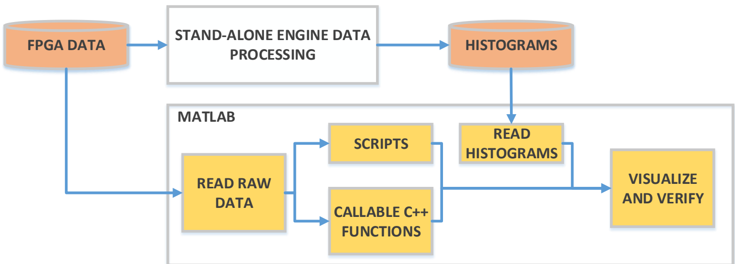

Fig. 4. Evaluation and Data Quality Monitoring (DQM) mechanisms provided within MATLAB and stand-alone engine. Files are marked in red, computation platforms are encased in white rectangles, functions are marked in yellow

The mechanism allowed to compare the split intermediate results and histograms from either of three methods of executing computations – the MATLAB reference scripts, the C++ functions callable via MATLAB and a stand-alone run. In the last case, the output can be loaded to MATLAB and evaluated.

4. The optimized back-end processing pipeline

Within the engine, the library of functions for splitting and histogram calculation has been implemented and optimized. Several performance issues have been spotted and overcame. First of all, the performance severely depended on the memory access pattern - acceleration was therefore achieved by fusing split, data grouping, cluster recognition and histogram calculation as presented in figure 5. A parallel algorithm was designed with a fork-join pattern, in which histograms were calculated for data within a particular time resolution quantum and joined.

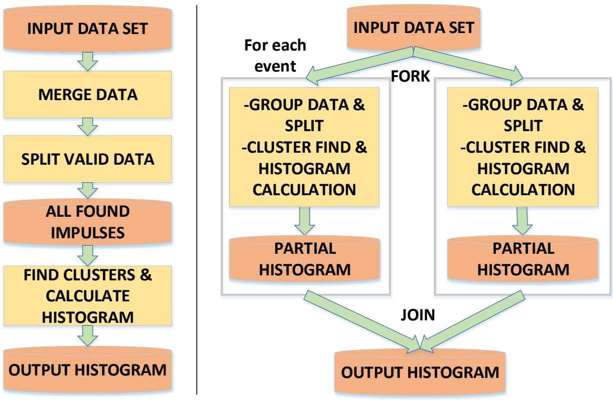

Fig. 5. Comparison of slow MATLAB algorithm and optimized parallel algorithm

The acceleration test was conducted with results in gathered table 1. For evaluation, the data set was chosen from the laboratory experiment with an X-ray source, containing 10 thousand events with approximately 5 million impulses. The mex functions and the stand-alone library were compiled with the gcc version 4.9.4-2 and ran in Linux Ubuntu 14.04 LTS, kernel version 3.19-031900-generic x86_64. The hardware was an Intel i5-4200 CPU@2500 MHz with 2x4 DDR3@1600 MHz operational memory. With the developed evaluation tools, full algorithmic compliance was proven between mex, stand-alone and MATLAB script by comparing the results. One can observe significant speedup over MATLAB script and mex functions. The run of an optimized engine was over 360 times faster than MATLAB run and over 10 times faster than the mex functions.

Table 1. Execution times of diagnostic algorithms – the MATLAB scripts, the mex functions callable from MATLAB and the stand-alone library parallel complete grouping, split and histogram calculation with 2 threads running.

Test Type	script split	mex split	script histogram	mex histogram	stand-alone group split and histogram
Duration [s]	133.7	9.0	194.5	0.8	0.9

The subsequent test was conducted to assess the achievable throughput and imposed latencies. A data set was chosen containing 200 thousand events with 105 million pulses (the high impulse rate was achieved as in previous experiment, by setting very for low trigger value).

A dual-socket server, designated for the deployment in the WEST was used with single Intel Xeon e5-2630 v4 CPU@2,2 GHz, 4x 16 GB DDR4@1866 MHz. The operating system was Centos 6.4, kernel 2.6.32-696.6.3.el6.x86_64, gcc version was 4.4.7 20120313. Two tests were conducted. In either all data were divided into 800 event chunks, each having approximately 4 MB of size (this was set in order to obtain an equivalent of approximately half a second of data from the FPGA front-end). For the first test 16 threads were running (i.e. number of logical cores of processor with hyper threading enabled). In the second test, only one thread was executing. The results are depicted in table 2. The processing of a single chunk lasted on average for 9 milliseconds when consuming all CPU cores and 42 milliseconds when single core was used. This is particularly important for future investigation of various computation distribution protocols within further research. This means that requested latencies are achievable The processing of 0.5 second of input data lasted for 2.2 second and has to be minimized. However, the impulses ratio has to considered as extremely high in this test– 4 pre channel per event.

16-thread execution [ms]	average 16-thread execution for single chunk [ms]	single-thread execution [ms]	average single-thread execution for single chunk [ms]
2200	9	10500	42

Table 2. The comparison execution times for single-thread and multi-thread run

The solution is easily scalable and it will be, within further research, further optimized. Dual-CPU server, Intel Xeon Phi, GPU are the currently-considered devices. The computations can also be moved to a multi-node platform with several servers. At the present stage, the solution proved itself feasible and will be further developed.

5. Conclusion

The stand-alone computation engine with fully-functional modes of operation has proven itself applicable. Optimization of plasma diagnostics algorithms has been achieved to an extent allowing the deployment in the WEST tokamak in CEA Cadarache, France. The software platform is contained within the diagnostic system deployed in CEA. Satisfactory acceleration level was achieved and further optimization is possible and pursued.

Acknowledgments

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