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ABSTRACT
Gamma-ray diagnostics are considered of crucial importance for understanding the plasma behavior of next fusion devices. Among other physical phenomena, gamma-ray spectra can provide information about the fusion reaction rate and the fast ions temperature and confinement, indicators of how close we are from reaching self-sustained burning plasmas. Accordingly, dedicated gamma-ray diagnostics are currently installed at the Joint European Torus (JET). The 2D gamma-ray profile monitor is one of these diagnostics, equipped with an Advanced Telecommunications Computing Architecture (ATCA) Data Acquisition (DAQ) system, capable of digitizing gamma-ray signals from the 19 photodiode detectors. The DAQ system includes Field Programmable Gate Array (FPGA) devices, with embedded processing algorithms. These algorithms are responsible for processing the gamma-ray signals acquired from each detector in real-time, and for periodically streaming the corresponding energy values to the DAQ host. However, for higher count rates it is unfeasible streaming periodically all the energy values without loss. Thus, a new algorithm was designed, capable to produce real-time spectra at FPGA from the processed energy values. The spectra should be periodically streamed, instead of energy values, ensuring no data losses. Consequently, the streaming data can be used for control purposes, as demanded by next fusion experiments with long plasma discharges of high energy/count rate content. This work describes the real-time spectrum code developed for FPGA along with the attained results. It was concluded that the spectrum code is suitable for implementation in any spectroscopy diagnostic, whenever real-time spectra are required.

1. INTRODUCTION
Confined alpha particles produced from $Deuterium - Tritium$ (DT) reactions should be responsible for the self sustained plasma heating of future fusion reactors [1]. It is expected that these alpha particles transfer their energy to the thermal plasma providing the necessary heating for a steady state operation [2]. Thus, understanding alpha particles behavior during DT experiments is of crucial importance to reach self sustained plasmas [3]. It is known that intense gamma-ray emissions can be measured during interactions between alpha particles (or energetic ions) and impurities, providing information about the fusion reactions rate [4]. Accordingly, gamma-ray spectroscopy is one of the proposed techniques for the measurement of alpha particles and fast ions (MeV range) populations in future plasmas. Furthermore, it is known that alpha particles and fast ions in plasmas may drive instabilities, potentially damaging their own confinement as well as the plasma confinement [2], [5]. Thus, measurements of gamma-ray emission in real-time are advantageous, guaranteeing the plasma confinement through a properly intervention in the instability source. Several dedicated Gamma-ray diagnostics were installed at JET, the only present machine that can confine fast ions (*MeV* range), produced by external sources (ICRF and NBI auxiliary heating sources) [6]. One of the diagnostics is the JET 2D gamma-ray profile monitor, composed by 19 Lines-of-sight to view the plasma through CsI(Tl) detectors. The diagnostic was recently upgraded with an Advanced Telecommunications Computing Architecture (ATCA) Data Acquisition (DAQ) system developed

by Instituto superior Te´cnico (IST). ATCA technology has been extensively used for control and DAQ systems of fusion experiments, being considered for ITER diagnostic systems targeting the plasma control [7]. The gamma-ray profile monitor DAQ system includes real-time processing and data transfer capabilities, allowing to process and stream periodically the gamma-ray energy values from the acquired signals during experiments [8]. However, streaming energy values requires count rate dependent packets which is not the optimal approach. Moreover, for high count rates it may be unfeasible streaming all energy values without losses. Accordingly, a new algorithm was designed capable to produce in the FPGA the energy spectra from the processed energy values. Thereby, the new streaming packet, with standardized size, should publish the energy spectra instead of the current energy values. This new algorithm will be relevant for future *DT* experiments where much higher count rates are expected. So far, the poor SNR and the CsI(Tl) detectors slow response limit the diagnostic performance to a maximum count rate of 20 *kevents/s*. However, this limitation should be improved by a foreseen set of new detectors.

In section 2 is presented the current diagnostic real-time pulse processing and data transfer architecture, in section 3 is described the developed FPGA real-time spectrum code and in Section 4 are depicted laboratory results.

2. THE REAL-TIME SYSTEM

The diagnostic DAQ system is composed by an ATCA shelf with 3 digitizer modules connected to a controller [9] through PCI-express (PCIe) links. Each digitizer module [10] includes eight 13-bit resolution Analog to Digital Converters (ADCs) with a maximum sampling rate of 250 *MSamples/s*, and two Field Programmable Gate Array (FPGA) devices (XC4VFX60). Besides the basic module functionality, FPGAs are used for real-time processing and deliver the energy values of acquired pulses. The system is also connected to the JET real-time network through an Asynchronous Transfer Mode (ATM) module installed in the ATCA controller. The ATM module allows publishing to the network packets with counts in established energy windows during discharges.

The interface to the JET Control and Data Acquisition System (CODAS), and to the JET real-time data network, is provided by the Multithreaded Application Real-Time executor (MARTe), the C++ framework installed in the ATCA controller under Linux OS with kernel version 2.6.35.9.

In figure 1 is depicted a schematic representation of the DAQ system and its interface to JET CODAS sub-systems.

As described in figure 2, for each JET shot the acquisition is enabled and the FPGAs start to process the incoming gamma-ray signals, calculating the corresponding energy values. Simultaneously, packets with the processed data are streamed from the digitizers to the ATCA controller. During acquisition, a total of five real-time packets with processed data are streamed, precisely at every 2*ms*, covering all the 19 CsI(Tl) signals. The total number of energy values per channel that can be transferred in each packet was set to $n = 247$, considering the maximum count rate of 20 *kevents/s*. The packets synchronization is guaranteed by JET absolute time signals connected to the master

FPGA. A dedicated software code running in the MARTe application is responsible for building calibrated spectra from the streamed energy values, and determine from each spectra the total counts in predefined energy windows.

However, for higher count rates the maximum number of energy values allowed in a single streaming packet may not be enough (e.g. 1 *Mevents/s* are expected during DT experiments, producing up to 8*k* energy values each 2*ms* per packet – 4 channels).

Thus, foreseeing count rate independent packets a new code was developed as detailed in section 3.

3. THE REAL-TIME SPECTRUM CODE

The developed real-time spectrum algorithm is capable of producing real-time spectra at FPGA from the processed energy values. As depicted in figure 3 diagram, each time an energy value is found the algorithm starts by determining the corresponding energy bin. Each energy bin corresponds to a different address in the FPGA spectrum buffer (SPECTRUM). Consequently, the SPECTRUM address found is incremented by one (SPECTRUM[addr]++). A total of 256 SPECTRUM addresses (energy bins) were defined. The maximum number of counts (energy values) per SPECTRUM address is 65 *K* (16-bit width). Periodically the SPECTRUM buffer is copied to an equal size buffer (SP) for serial streaming. When all SP buffer addresses were streamed a new SPECTRUM buffer copy is made (SP=SPECTRUM), the SPECTRUM data is deleted, and the process repeats.

To avoid using floating points at FPGA the streamed spectra are uncalibrated. Therefore, host is responsible for converting the spectra bins in energies range from estimated calibration slopes.

Depending on the required energy resolution, the energy bins window may need to be adjusted. This can be done through a compromise between energy windows and total energy range, without changing packets size. As example, for higher spectra resolution the energy bins window should be reduced as well as the total SPECTRUM energy range, keeping the SPECTRUM addresses number.

4. RESULTS

The developed spectrum code was tested in laboratory. For that purpose it was used the KC705 developing kit from Xilinx with an embedded Kintex-7 FPGA. The KC705 board is connected through an x4 PCIe link to the host PC. Two different experimental setups were used to simulate data from ADCs.

In the first setup were used energy values stored in one of the FPGA embedded blocks of memory (BRAM). Those energy values were obtained by the profile monitor DAQ system, in presence of ^{22}Na and ^{137}Cs radioactive sources. The ^{22}Na source, embedded in the detectors set, emit two gamma-ray peaks at $511keV$ and $1275keV$, and the ^{137}Cs source, embedded in collimators near detectors, emit a $662keV$ peak. During operation the FPGA code receives the energy values stored in BRAM and finds the corresponding energy bin in the spectrum addresses. The resulting spectrum is periodically streamed to the host PC as described in section 3. In figure 4 is depicted one of these real-time spectra where are visible the three expected energy peaks. Moreover, it is possible to conclude that real-time spectra are similar to results obtained by offline analysis detailed in section 2. It is important to remark that limited detection efficiencies are expected from gamma-ray profile monitor energy values. The spectral lines resolution is affected by the tokamak geometry, uncertainty due to the nonlinear response of CsI(Tl) detectors, the absorber materials in each Line-Of-Sight (LOS), and low counting statistics [11], [12].

For the second setup were defined energy values corresponding to 3 different energy peaks using FPGA counters. The peaks frequency relation is: $f_3 = 1/3\, f_2 = 2/3\, f_1$. As depicted in figure 5 real-time spectra delivered by FPGA agree with expected results.

An offline software code was used to calibrate real-time spectra of both setups.

5. CONCLUSIONS

The developed FPGA code is capable of determining energy spectra from energy values in real-time. Thus, the algorithm allows to have count rate independent packets ensuring no data losses. Moreover, the spectrum energy resolution can be optimized by reorganizing the streaming packets structure without changing its size.

This spectrum code is relevant for future DT experiments at JET, as well as for future fusion diagnostics expecting high event count rates. Furthermore it is suitable for implementation in other spectroscopy applications whenever real-time spectra are required.

The code was tested in the KC705 development kit from xilinx. The kit FPGA is different from the JET DAQ system FPGAs. As so, the code performance must be tested on-site when implemented. Nevertheless, the KC705 Kintex FPGA is fully compatible with the new ultra fast ATCA Advanced Mezzanine Card (AMC) FPGA developed by IST. This AMC was specially conceived for real-time spectroscopy applications expecting high event count rates [13].

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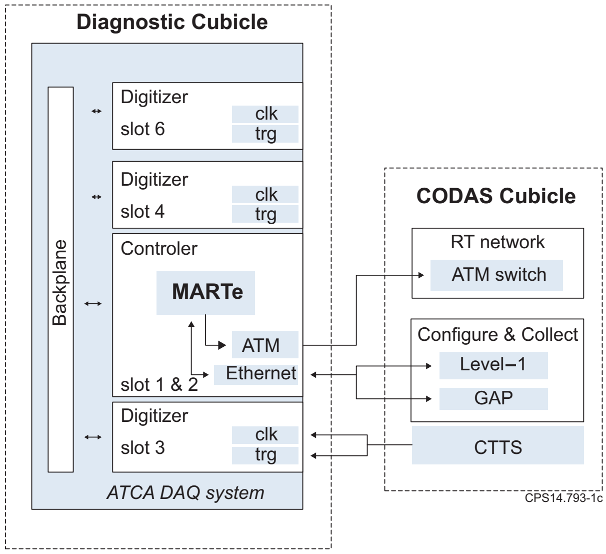

Figure 1: schematic representation of the DAQ system and its interface with JET CODAS sub-systems (diagnostic configuration (Level-1), data collection (GAP), ATM network, JET absolute time (CTTS).

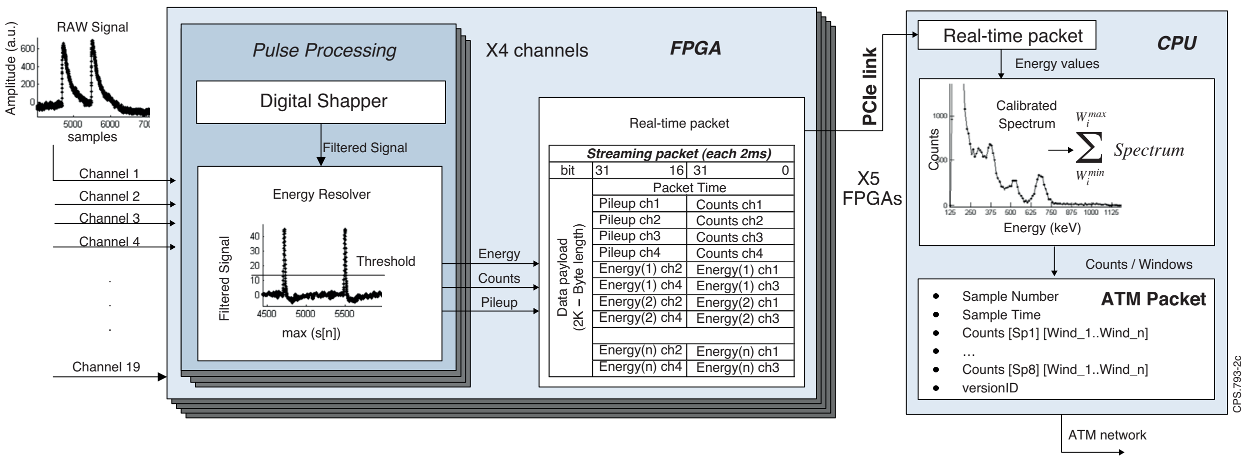

Figure 2: Flowchart describing DAQ signals data path. Data is acquired, processed in FPGA and streamed in every 2ms to the controller. In the controller side calibrated spectra are produced with streamed data, and counts in interesting energy windows delivered to the real-time network.

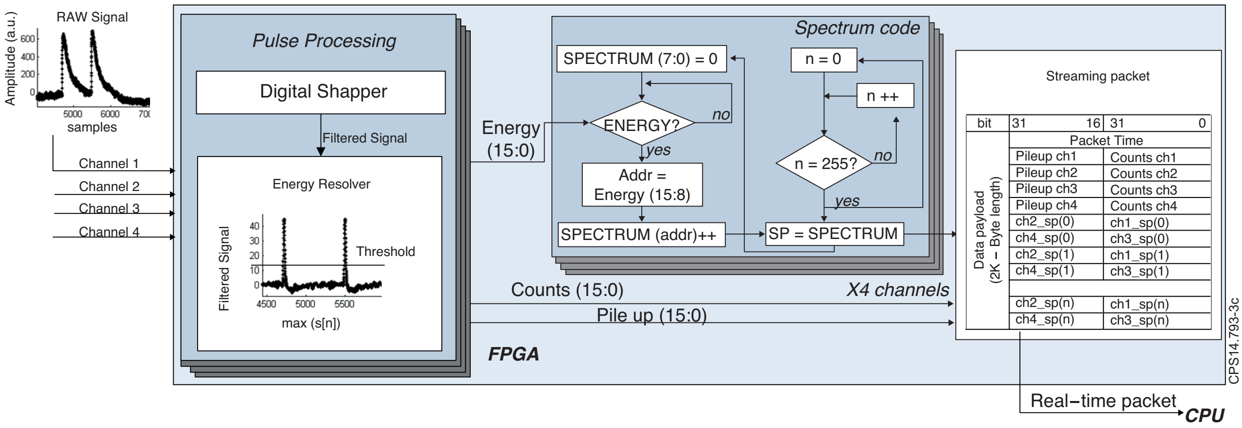

Figure 3: Spectrum code diagram. FPGA receives the digitized signals. When a pulse is found its energy value is calculated and the correspondent spectrum address (SPECTRUM[addr]) is incremented by one. Periodically (when n = 255) the produced spectrum is copied to an equal buffer (SP) which is streamed from FPGA to host.

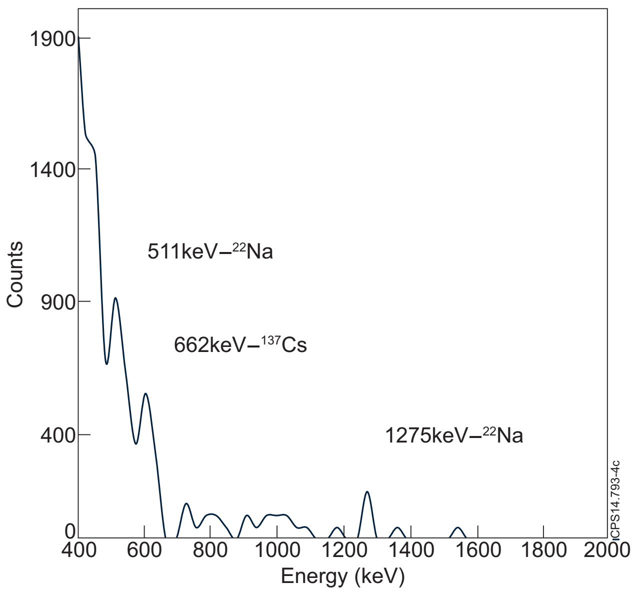

Figure 4: Real-time spectrum from KC705 FPGA real-time code. For input data were used energy values acquired with the profile monitor in presence of ^{22}Na and ^{137}Cs radioactive sources. The expected 511, 662 and 1275keV are visible.

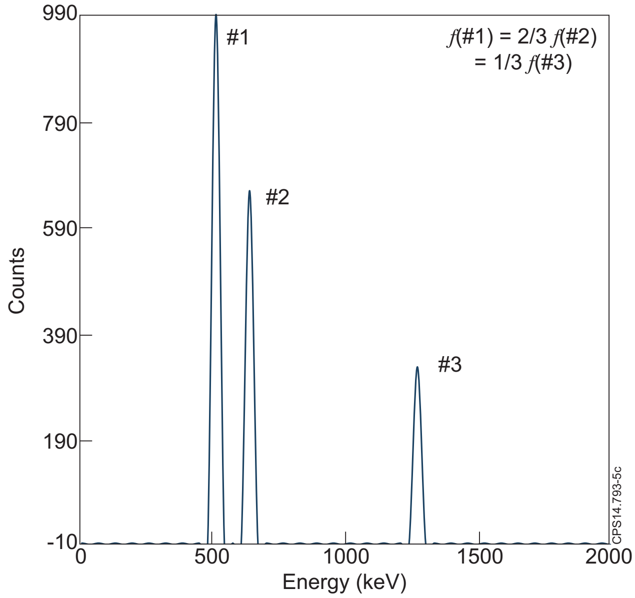

Figure 5: Spectrum from FPGA simulated data. Three different peaks were defined according with the following frequency relation: $f_3 = 1/3\, f_2 = 2/3\, f_1$.