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ABSTRACT

The Joint European Torus (JET) is currently undertaking an enhancement program, in which one of the objectives is to test relevant diagnostics for the International Thermonuclear Experimental Reactor (ITER), the reference for the next generation of fusion experiments. One of the challenges in ITER is the provision of real-time data analysis and compression capabilities, to sustain the expected long duration discharges and the high acquisition rates achieved by recent data acquisition systems. Foreseeing this real-time requirement, a new system was developed and installed at JET for the gamma-ray and hard X-ray profile monitor diagnostic. The new system, which is connected to 19 CsI(Tl) photodiodes in order to obtain the line-integrated profiles of the gamma-ray and hard X-ray emissions, was designed to overcome the data acquisition limitations of the present Fast Electron Bremsstrahlung diagnostic (FEB), while exploiting the required real-time features. This paper presents the real-time processing architecture for the JET gamma-ray and hard X-ray profile monitor. The system hardware, based on the Advanced Telecommunication Computer Architecture (ATCA) standard, includes reconfigurable digitizer modules with embedded Field Programmable Gate Array (FPGA) devices capable of acquiring and simultaneously processing data in real-time from the 19 detectors. A suitable algorithm was developed and implemented in the FPGAs, which are able to deliver the corresponding energy of the acquired pulses, and its associated occurrence time. The real-time processed data is sent periodically, during the discharge, through the JET real-time Asynchronous Transfer Mode (ATM) network, and stored in the JET scientific databases at the end of the pulse. Publishing the processed data in the ATM network enables it to be used for machine control purposes (e.g. the information about the line-integrated emissions of the hard X-rays in real time can be used to determine the lower hybrid current drive deposition before the main heating phase). Additionally, the real-time processed data is used for local calibration, using embedded radioactive sources to build in real-time the 19 channels spectra. The acquired raw data is also stored in the digitizer modules' local memory and retrieved after the pulse to the JET database, where it can be post-processed offline to validate the real-time algorithms. The interface between the ATCA digitizers, the JET Control and Data Acquisition System (CODAS) and the JET real-time network is provided by the Multithreaded Application Real-Time executor (MARTe). From the experimental results it was concluded that it is possible to measure in real-time the line-integrals of both hard X-ray and gamma-ray emissions, covering energy range from ~200keV to 8MeV. This allows us to meet two of the major milestones: the ability to process and supply high volume data rates in real-time over a wide spectrum energy range.

1. INTRODUCTION

HE next generation of fusion devices will require a more demanding and efficient data handling capability when compared with the existing devices [1]. The expected duration of the discharges, and the high acquisition rates of the diagnostics, makes it unfeasible to store all the data only after the end of the discharge for posterior processing. Real-time mechanisms must be available to guarantee the storage of useful information during all the discharge for physical studies [1,2].

Moreover, new real-time feedback systems are needed for a fast intervention in the plasma control, driven by the complexity and potential risks of the expected plasmas of higher energy content and longer duration [1].

The Joint European Torus (JET) gamma-ray and hard X-ray profile monitor enhancement diagnostic is part of a package of diagnostic enhancements dedicated to the preparation of the International Thermonuclear Experimental Reactor (ITER). The objective is to provide enhanced real-time tools capable of optimizing the plasma control during operation and enabling advanced control schemes for the main plasma scenarios and for particular profile controls [3]. To fulfill the enhancement requirements by exploiting real-time features, while overcoming the data acquisition limitations of the present Fast Electron Bremsstrahlung diagnostic (FEB), a new data acquisition system (DAQ), based in the Advanced Telecomunication Computer Architecture (ATCA), was developed and installed at JET for the gamma-ray and hard X-ray profile monitor diagnostic [4]. The DAQ system uses reconfigurable digitizer modules with embedded Field Programable Gate Array (FPGA) devices, well know from literature for its real-time capabilities [5,6], allowing the implementation of real-time processing algorithms. The Multithreaded Application Real-Time executor (MARTe) [7], a C^{++} framework used in several fusion machines and installed in the DAQ system, allows the exploitation of the real-time features, by providing the interface to the JET Real-Time Asynchronous Transfer Mode (ATM) network.

This paper describes the new real-time processing architecture, implemented for the JET gamma-ray and hard X-ray emission profile monitor DAQ system. In section 2 is presented a brief description of the system hardware; sections 2 and 3 describe the implemented functionalities in the digitizers modules FPGA's (firmware code); and sections 4 and 5 explains the functionalities achieved by using MARTe framework (software code). Results and conclusions are presented in chapters 6 and 7, respectively.

2. DAQ SYSTEM HARDWARE

The JET neutron/gamma-ray/Hard X-ray emission profile monitor provides 19 Lines Of Sight (LOS), 9 through the vertical port and 10 through the horizontal port, for viewing the plasma. Each LOS is composed by a set of three different detectors to monitor a wide energy spectrum resulting from neutron, gamma-ray and hard X-ray in the plasma. One of the detectors, a CsI(Tl) scintillator coupled to a photodiode detector, is used to measure the gamma-rays and the hard X-rays, resulting from the FEB, in a range from 200keV to 6MeV [8]. The pulses returned by the CsI(Tl) photodiode have an exponential shape and the former system uses an analogue spectroscopy shaping amplifier that amplifies and shapes the signals to a Gaussian format before sending it to the Pulse Height Analysis (PHA) instrumentation – a MultiChannel Analyzer (MCA). The MCA accommodates the gamma-ray count rate in four energy windows [8, 9]. Both hard X-ray and gamma-ray radiation could not be obtained simultaneously in the same experiment and the produced data was not output to the JET ATM network.

The new ATCA DAQ system was installed to replace the former system (shaping amplifier +

MCA), being able to acquire the line-integrated emissions of the hard x-ray (low-energy pulses) and the gamma-ray (high energy pulses) simultaneously, achieving a single spectrum for all the energy range. The system is composed by: (i) an ATCA shelf; (ii) an ATCA controller module; (iii) three ATCA digitizers modules; and (iv) one PCI/ATM module. The controller module is an Intel Core$^{(TM)}$ 2 duo E7400 @ 2.8GHz ×86-based General Purpose Processor (GPP), composed by an Advanced Technology Extended (ATX) motherboard linked to a PCI Express (PCIe) switch through x16 PCIe lane [10]. Each ATCA digitizer module is composed by eight analog to digital converters (ADC) with a maximum sampling rate of 250 Msamples/s, of local memory (DDR2) and two Virtex-4 FPGAs [4]. A total of three digitizer modules are needed to accommodate data from all the 19 CsI(Tl) detectors. The PCI/ATM is a PROATM-V155 module from PROSUM and is the interface to the JET ATM network.

3. DAQ SYSTEM FIRMWARE

Each FPGA embedded in the digitizer modules is physically connected to four ADCs, two GB of DDR2 and one PCIe physical link. The FPGAs are responsible for implementing most of the module functionalities such as: (i) triggering and clock management; (ii) interface with DDR2; (iii) gigabit communication through PCIe links with the ATCA controller; (iv) data path from ADCs to local memory and to PCIe links.

A suitable code, depicted in Fig. 1, was implemented in the FPGAs to fulfill these functional requirements. A real-time algorithm adequate to process the gamma-ray and hard X-ray signals coming from the CsI(Tl) detectors was also implemented in the FPGA. The algorithm was adapted from the trapezoidal filter, a well-known algorithm used in spectroscopy to analyze exponential signals with a fast positive step (rise time) followed by a long decay step (decay time) [11]. The amplitude of the fast step, of the pulses returned by the CsI(Tl) photodiode, is proportional to the energy deposited by the gamma-ray (high energy pulses) and the hard X-ray (lower energy pulses) in the detector. When a pulse is detected, by applying a predefined threshold to the filtered signal, the process module (PROCESS in Fig.1) delivers a 64-bit word, with the energy of the pulse and the corresponding time occurrence.

According to experimental results it was observed that the received signal is very noisy, mainly due to the cabling (80m coaxial cable), the associated electronics and the intrinsic noise of PIN photodiodes (unitary gain). Moreover, it was concluded that, due to the poor signal to noise ratio, associated with the larger pulses presented by the detector (rise time of 200ns and pulse duration >400us), the maximum ADC sampling rate is not adequate for sampling the signals. The sampling rate of the acquired data was reduced to 2.5MHz, by reducing the ADC sampling rate (50MHz is the minimum ADC sampling rate) and by implementing a Finite Impulse Response (FIR) decimator for each ADC input data. Downsampling the signal and running the FIR filter enables to increase the effective number of bits and to make the pulses with less resolution more visible.

4. FIRMWARE DATA PRODUCTION

When an acquisition is enabled, real-time Direct Memory Access (DMA) packets with real-time processed data are streamed, precisely at every 2ms, through PCIe links from the digitizers FPGAs to the ATCA controller (RT PACKET in figure 1). Each streamed packet is 2K-Byte length, carrying information from the four ADC channels. The streamed packet, illustrated in Fig.2, is composed by: the packet time in microseconds, related to the start of acquisition; the total energy values for each channel; the number of pileup counts obtained in each channel; and a vector with energy values achieved for each channel. Due to the maximum count rate (20kevents/s) limited by the detectors response, the maximum number of energy values was set to n = 228. A total of five packets are streamed every 2ms to the ATCA controller, covering all the nineteen CsI(Tl) signals.

Additionally, and depending on the user choice in the plant system configuration (see section V), two different data types can be stored during the experiment in the digitizers DDR2: (i) raw data, with a 16-bit word length for each sample (Fig. 3.a) or (ii) processed data, with a 64-bit word length for each sample, corresponding to the energy value and its related time occurrence (Fig.3.b). When the acquisition is disabled, usually triggered by the end of the experiment, the digitizers stop sending streamed data and start sending PCIe DMA packets with the data stored in DDR2 to the ATCA controller. At the end of each DMA packet a Message Signaled Interrupt (MSI) is sent to acknowledge the host about the reception of new data (valid for both DMA streamed data and DMA with DDR2 data).

5. DAQ SYSTEM SOFTWARE - MARTE

MARTe is a C++ data driven multi-platform framework environment that standardizes the development of real-time control systems and provides standard interfaces for development, commissioning and deployment of the systems [7]. The MARTe application, shown in Fig.4, is installed in the ATCA controller, and it is responsible for interfacing with the DAQ system, the JET control and data acquisition system (CODAS) and the JET real-time ATM network system. A series of Generic Application Module's (GAM), the core component of MARTe, are used to implement the control and data processing algorithms. The signals between GAMs are shared by a memory data bus, named Dynamic Data Buffer (DDB). Two special modules, called IOGAMs are also used for interfacing the hardware with MARTe. The ATCA IOGAM was developed to interface with the digitizer modules providing the configuration parameters, receiving the time synchronization, and managing the received DMA real-time packets. The ATM IOGAM is used to interface with the ATM module and delivering the calculated set of signals (datagrams) to the JET ATM network. Additional modules are also present in the application to translate the JET standard tools and protocols into the MARTe language. In particular the following MARTe modules are used: (i) translator from the pulse schedule editor for system plant configuration in the control room (Level-1); (ii) data retrieval for the data downloading and archiving by the JET General Acquisition Program (GAP) data archive system; and (iii) the Signal Archiver to physically store in the local disk the real-time streamed data for posterior GAP collection.

A copy of the real-time streamed data, and the DDR2 data, are collected by GAP and archived in the JET database. The GAP will collect a total of 78 signals upon the termination of the pulse. 19 correspond to DDR2 data. 58 are the streamed signals separated by data type (i.e. total counts, pile-up, energy values and time). The separation in data type is performed by the ATCA IOGAM. The last signal is the overall cycle time measured by MARTe to check if the 2ms set for running all GAMs and synchronizing with the next cycle is being fulfilled. Meeting the timing requirements and not losing packets is the basis for a real-time system. In Fig.5 is showed the overall cycle time measured for a single experiment. A maximum jitter of 37us was achieved, confirming the system resilience required for a real-time system.

6. ATM DATAGRAMS

The main purpose of connecting the system to the JET ATM network is to use the datagram signals for real time control, by delivering it to an appropriate actuator [12]. A possible application can be to determine in real-time the Lower Hybrid Current Drive (LHCD) deposition profile before the main heating phase, from the amount of hard X-rays generated by bremsstrahlung process when an LH wave is injected in the plasma [13]. To demonstrate the capability of publishing the processed data in the ATM network to be used for machine control purposes, a generic datagram with 8 signal vectors of fixed size, contains the number of counts achieved in a pre-defined number of energy windows. This allows to broadcast up to 8 of the available 19 channels, each with its single energy window configuration, or to repeat the same channel over a larger number of time windows. For this purpose a new generic GAM called Spectrum-GAM was developed, as described in Fig.6. The GAM receives the energy values of a single channel, extracted by the ATCA IOGAM from the streamed packet, builds the histogram, calibrates the histogram in counts/energy by using a pre-defined calibration slope achieved for each channel, and finally calculates the total counts for each pre-defined energy window. The choice of using a different Spectrum-GAM instance for each channel, instead of a single GAM for all the channels increases the flexibility of using different number and values of energy for each selected channel.

Up to 8 Spectrum-GAMs are used by the MARTe application to publish the energy counts in the ATM network. The output signals from these GAMs are inputs of the ATM-IOGAM, were the ATM datagram structure (showed in Fig. 6) is defined.

7. RESULTS

The real-time processing architecture for the JET gamma-ray and hard X-ray emission profile monitor, described in the previous sections, was implemented and tested. For system validation with calibration sources three different radioactive sources were used: (i) a ^{22}Na source embedded in the detectors module, emitting two gamma-ray peaks at 511keV and 1275keV; (ii) a ^{137}Cs source embedded in collimators, placed near the detector, emitting a 662keV peak; and (iii) a movable 241Am-Be source, inside the detectors module, producing gamma-ray during the decay of the ^{12}C* resulting from the reaction ^{9}Be(n,α)^{12}C* (photopeak at 4.4MeV, Single Escape (SE) peak at

3.9MeV and Double Escape (DE) peak at 3.4MeV). With the movable 241Am-Be source, gammas resulting from the capture of thermal neutrons by existing nuclides (6.8MeV and 7.1MeV), were also produced. Calibrated spectra were produced for each channel with the real-time processed data acquired locally. Due to the low activity of the embedded sources (~25 counts/s for ^{22}Na and ^{137}Cs and 700 counts/s for ^{241}Am-Be), 20 minutes of acquisition were needed to build a spectra for each channel with enough statistics, requiring real-time processed data. As an example Fig.7 shows spectra obtained with the calibration sources for channel three, evidencing the referred gamma-ray peaks. The ^{137}Cs backscattered peak and the 511 keV ^{22}Na were used to determine the lower energy limit for each detector. The movable 241Am-Be source was used to validate the system for high energies. From the experimental results, obtained with radioactive sources in laboratory it was concluded that the same DAQ system is suitable to measure both hard X-ray and gamma-ray, covering an energy range from ~200keV to 8MeV.

The system is being tested during the C28, C29 and C30 JET campaigns. The information about the gamma-ray and the hard X-ray emission profiles can be obtained, between experiments, using the real-time signals stored in JET database, and the calibration slopes achieved from spectra obtained with the radioactive sources. Some of the available information is: (i) calibrated spectra, (ii) counts in pre-defined energy windows (iii) counts in time-windows and (iv) counts/time.

As an example, in Fig.8 is showed the total number of counts as function of time obtained for channel 14 during the JET Pulse No: 81892. As expected, the number of pulses increases when the Neutral Beam Injection (NBI) and the LHCD were launched. Mainly due to the low Ion Cyclotron-Resonance Heating (ICRH) power achieved during campaigns, the occurrence of gammas by the interaction of fast ions with fusion products and impurities [8] was not sufficient to obtain relevant spectra with gamma-ray induced by fast ions. However the response of the system during discharges agrees with the expected results, as showed in the spectra from Fig.9, where the consistence of results obtained for discharges with a similar setup is evidenced.

The ATM connection was tested, demonstrating the capability of publishing the processed data in the ATM network. Fig 10 shows the ATM signals obtained for Pulse No: 83082, corresponding to counts in 8 distinct windows for channel 2. The number of counts is inversely proportional to the correspondent energy window as expected when the presence of gamma-ray resulting from fast ions is very limited, due to the low heating power used.

The raw data stored in local memory (raw acquisition option chosen in system plant configuration) was used to validate the processed real-time data.

CONCLUSIONS

The new data acquisition system presented in this paper, installed for the JET Hard X-ray and Gamma-ray profile monitor, allows overcoming limitations of the former data acquisition system. It is now possible to achieve continuous and simultaneous spectra for both hard X-ray and gamma-ray signals in an energy range from ~200keV to 10MeV. The system is now connected to the real-time network. The counts in pre-defined energy windows of the most relevant channels, obtained from the streamed processed data coming from the FPGA´s, are used to build an ATM datagram to be sent periodically (each 2ms) through the JET ATM network. The streamed data and the ATM packets are available in JET database at the end of the discharge for data comparison. Concerning the data stored at local digitizers memories and retrieved after the end of the experiment, can be used for comparison with the streamed data, after applying an adequate (off-line) algorithm, for validation purposes.

The exploited real-time features presented by the system meets the requirements for next fusion devices including ITER, being capable to supply real-time processed data during the experiment. One of the diagnostic limitations is the poor signal to noise ratio. With a new set of detectors and improvements on cabling, the system could process data at its maximum sampling rate (250Msamples/s), increasing the count rate and the diagnostic performance. One improvement foreseen, required if the acquisition rate increases, is producing a real-time algorithm inside FPGA capable to deliver directly the histogram instead of the energy values. Another foreseeing improvement is developing a new code to produce in real time the tomographic reconstruction of the hard X-ray and gamma-ray deposition profiles. This information could also be used for control purposes by sending it through the ATM network.

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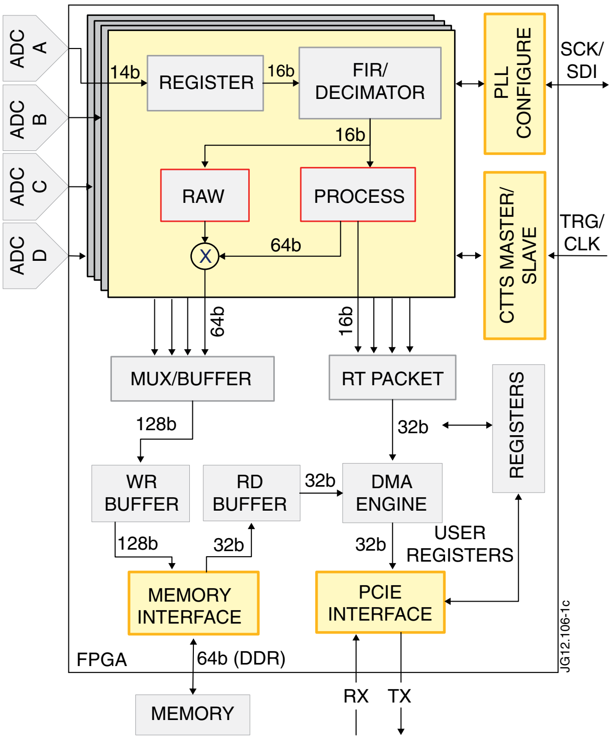

Figure 1: Schematic representation of the FPGA code, represented by individual modules, and the path imposed to the received data, represented by wire connections between modules.

Streaming Packet (each 2ms)

{
- Packet Time (32-bit)
- Pileup 1 (16-bit); ToTCounts 1 (16-bit)
- Pileup 2 (16-bit); ToTCounts 2 (16-bit)
- Pileup 3 (16-bit); ToTCounts 3 (16-bit)
- Pileup 4 (16-bit); ToTCounts 4 (16-bit)
- Energy Value 2 [1](16-bit); Energy Value 1 [1](16-bit)
- Energy Value 4 [1](16-bit); Energy Value 3 [1](16-bit)
- ….
- Energy Value 2 [n](16-bit); Energy Value 1 [n](16-bit)
- Energy Value 4 [n](16-bit); Energy Value 3 [n](16-bit)

}

Figure 2: Streaming data packet structure. The numbers 1, 2, 3 and 4 correspond to the channels number and n is the maximum size for the energy vector. If the maximum number of energy values is not achieved, the remaining vector values are filed with zeros. A total of five simultaneous packets are streamed to cover the nineteen channels.

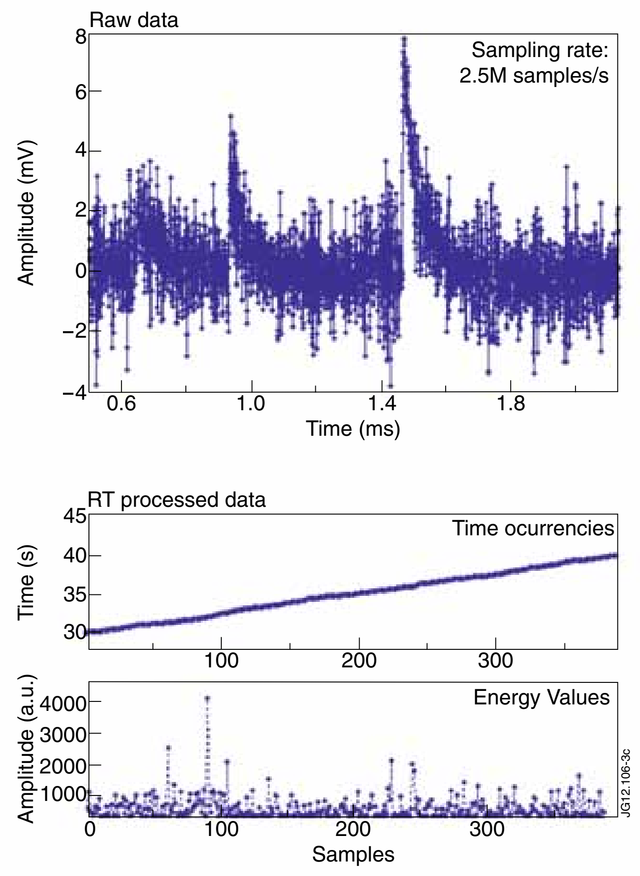

Figure 3: The two data types that can be delivered from the FPGAs: a) raw data with a 16-bit word length each sample; b) processed data (energy value + time occurrence) with a 64-bit word length each sample.

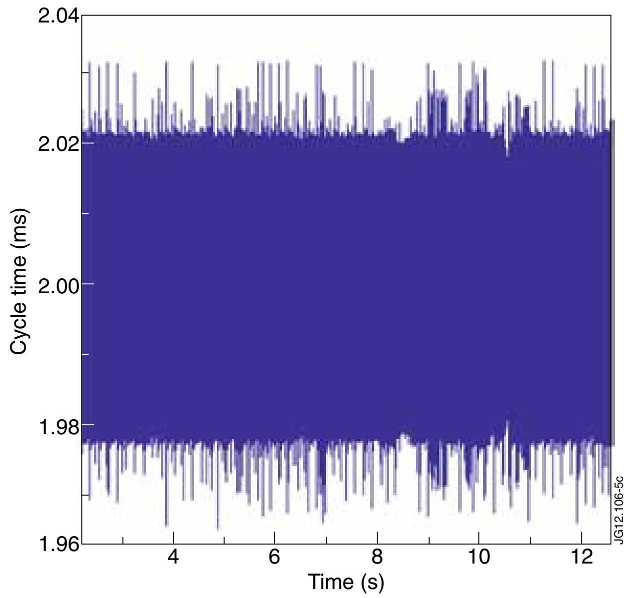

Figure 5: The overall cycle time measured by MARTe during a discharge. The system is running in a Intel® coretm 2 duo with Linux® and with an isolated CPU for MARTe's real time thread. A maximum jitter of 37us was obtained.

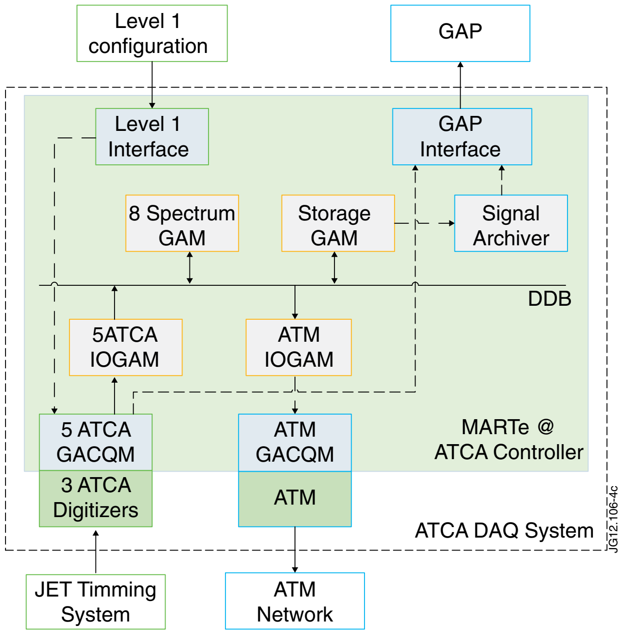

Figure 4: MARTe application diagram for the JET gamma-ray and hard X-ray emission profile monitor. The hardware interface to the configuration plant is based on PCIe and ATCA standards.

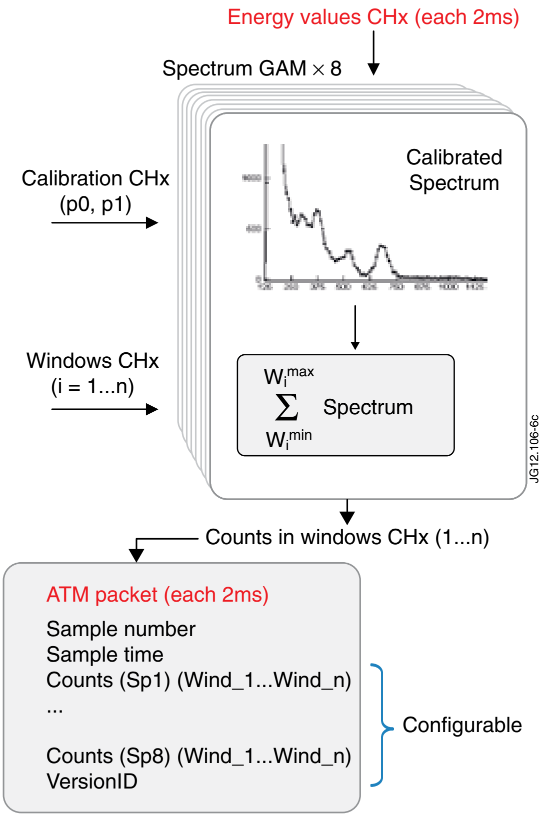

Figure 6: Schematic representation of the Spectrum-G AM code and the ATM packet structure to be published in the ATM network. CHx corresponds to the channel number; n is the number of windows (minimum and maximum values) defined for each channel.

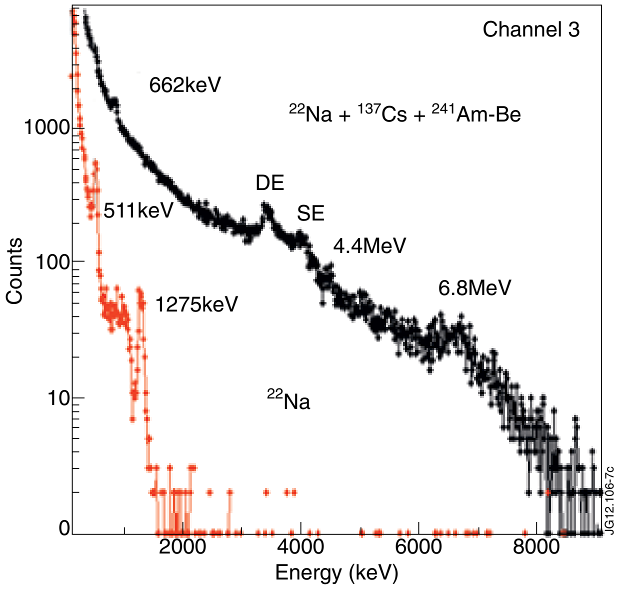

Figure 7: Spectra built with real time processed data inside FPGA using the embedded 22Na, 137Cs and a movable 241Am-Be radioactive sources.

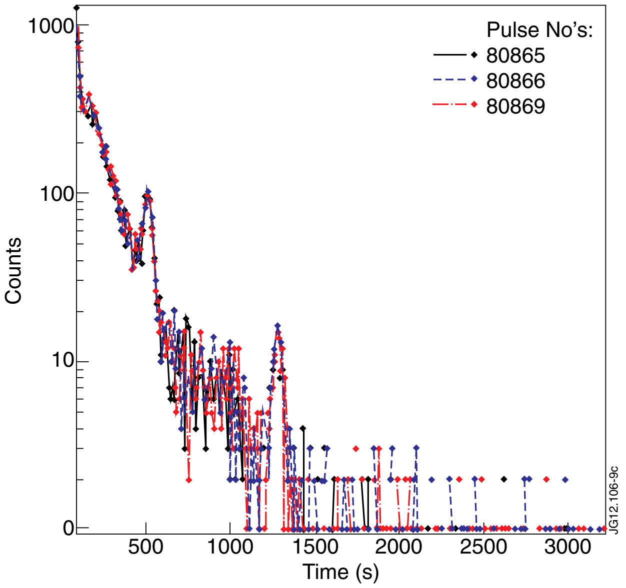

Figure 9: Spectra obtained during C28 campaign for channel 11 at the Pulse No's: 80865, 80866 and 80869, showing the consistence in the system response for similar setups.

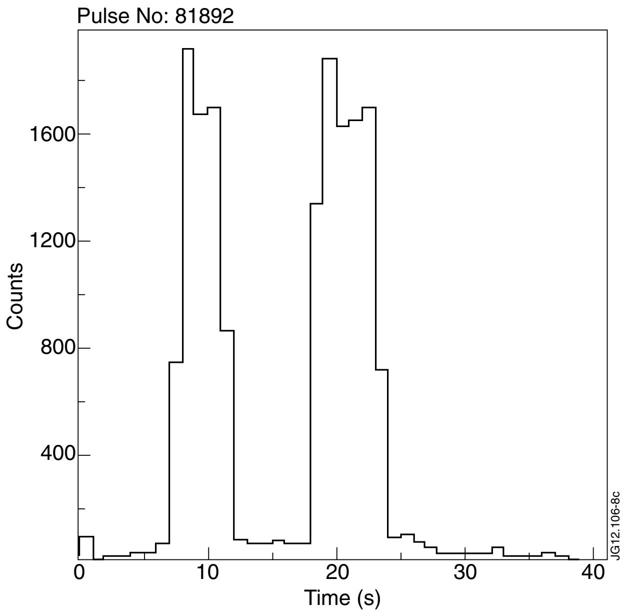

Figure 8: The total number of counts as function of time obtained during the Pulse No: 81892 for channel 14. The NBI was launched in time window from 7s to 12s and the LHCD in time window from 18s to 23s. As expected, the number of pulses increases when the NBI and LHCD were launched.

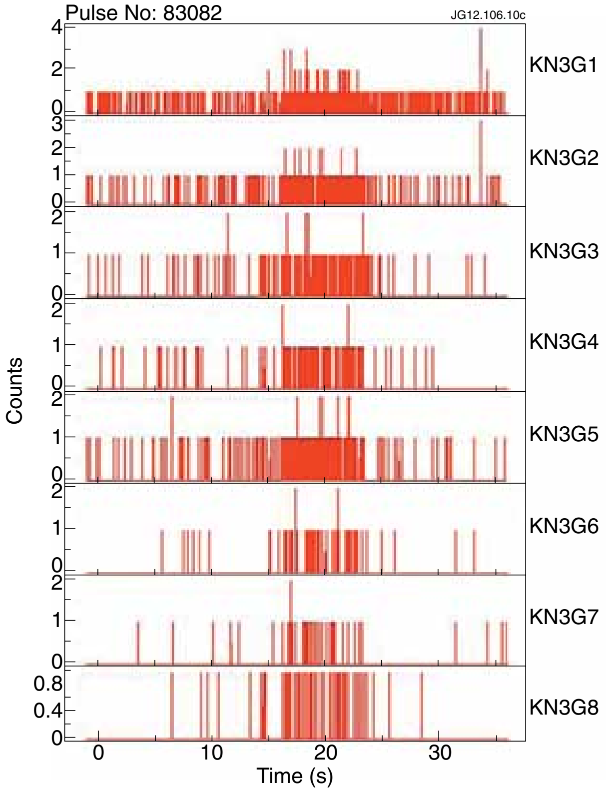

Figure 10: ATM signals obtained for Pulse No: 83083 corresponding to counts in eight distinct windows for channels 2. The set windows, starting from the top to the bottom are: 125-225keV; 225-300keV; 300-375keV; 375-450keV; 450-720keV; 650-790keV; 1200-1350keV; 1550-2350keV.