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ABSTRACT

The duration of a single plasma discharge in next generation of fusion experiments will be much longer than in the present devices. Storing all raw data acquired in each discharge will be more difficult and the high rates achieved by the new digitizers are already contributing to storage overload. The problem can be mitigated by Real Time (RT) analysis and compression, using devices such as FPGAs capable to transfer and process data on the fly. To ensure a correct RT analysis, the FPGA algorithm must be adapted to the signal to be acquired. It is important to know in advance the signal attributes as minor changes in signal shape may require significant algorithm modifications. For that reason, the availability of more than one RT algorithm is important, especially during commissioning of new sub-systems and during campaigns with relevant changes in diagnostic conditions. This paper presents an implementation using two RT algorithms processing simultaneously, developed for the gamma-ray and hard X-ray diagnostics of the Joint European Torus (JET). Both algorithms perform pulse height analysis with pile-up rejection. The first algorithm is suitable for Gaussian shaped pulses and the second is suitable for exponential signals. The algorithms are selectable by the user, during discharge configuration. Tests made at JET with radioactive sources are presented.

1. INTRODUCTION

Real Time (RT) analysis and compression became a challenge research field for next generation of fusion experiments [1]. To cope with the high acquisition rates and long discharge times, the huge amount of raw data produced in a single discharge must be reduced locally to useful information before being stored for analyses and used for control [2]. The reconfigurable Field Programmable Gate Array (FPGA) devices, present in data acquisition hardware modules, are capable to processes the acquired raw data in RT, returning only the useful information [3]. However, the RT algorithm in the FPGA must be adapted to the expected signals guaranteeing a correct RT analysis. Moreover, the algorithm must be flexible to cope with predictable signal fluctuations. In some diagnostics the availability of more than one RT algorithm is beneficial due to signal shape fluctuations. Notwithstanding, changing the firmware between shots is impracticable and not allowed during normal operations. The solution can pass through the implementation of different selectable algorithms in the FPGAs, to comply with the predictable changes in the signal shape. The signals coming from the JET gamma-ray/hard X-ray profile monitor are a good example. The signal shape changes from exponential to Gaussian when using an analog external shaping amplifier [4]. In this work, two algorithms for spectroscopy analysis were developed and implemented simultaneously in the FPGAs of the new ATCA digitizer system of the JET gamma-ray/hard X-ray profile monitor diagnostics. In section 2 the two RT algorithms are described; in section 3 the FPGA code of the new digitizer system from JET is presented; and in the section 4 some laboratorial results are shown.

2. REAL TIME ALGORITHMS FOR SPECTROSCOPY

FPGA devices can perform multiple tasks, including different RT algorithms processing the same data simultaneously. The data inside the FPGA follow a first in first out philosophy which avoids resources consuming on storage for further analyses, allowing the return of useful information in RT. The two algorithms, suitable for spectroscopy analyses, were developed in VERILOG language. Both algorithms perform Pulse Height Analysis (PHA) with Pile-Up Rejection (PUR) and can be applied to pulse signals, whose amplitude is proportional to the energy deposited by the corresponding gamma-ray or X-ray photon interacting in the detector [4]. The first algorithm is used when Gaussian shaped pulses are acquired (section 2.1) and the second when exponential pulses are expected (section 2.2).

2.1 ALGORITHM FOR GAUSSIAN SHAPED PULSES

An external shaping amplifier can be used between the detector/preamplifier and the PHA instrumentation due to the following reasons: i) to improve the poor signal to noise ratio presented by the signals coming from the detection system; ii) for baseline restoration; and iii) for pile-up rejection [4,5]. A common pulse shape returned by the shaping amplifier is a Gaussian or semi Gaussian [5]. The Gaussian amplitude is related to the energy of the corresponding photon that interacts in the detector.

A RT algorithm implemented in the FPGAs was developed to determine the amplitude of a Gaussian shaped pulse. In figure 1 a schematic view of this algorithm is presented. After a predefined threshold the algorithm starts to find the maximum of the amplitude and, if another maximum does not occur during the expected duration of the pulse (predefined value), the achieved maximum amplitude is stored with the corresponding timestamp (occurrence time).

2.2 ALGORITHM FOR EXPONENTIAL SIGNALS

A common pulse shape returned by the gamma-ray/X-ray preamplifiers is similar to an exponential signal with a fast positive or negative step (rise time) followed by a long decay step (decay time) [4]. The amplitude of the fast step is proportional to the energy deposited by the gamma-ray/X-ray in the detector [4]. The trapezoidal filter is a well known algorithm used in spectroscopy to analyze exponential signals [6]. The exponential signal is transformed into a trapezoid by series of differentiators and integrators. The difference between the flat top of the trapezoid and the base of the trapezoid corresponds to the pulse energy [6].

A RT algorithm based on a trapezoidal shaper implemented in the FPGAs was developed to determine the amplitude of an exponential pulse [7]. A scheme of this algorithm is presented in figure 2.

3. JET GAMMA-RAY/HARD X-RAY PROFILE MONITOR

The JET neutron emission profile monitor is composed by 19 lines of sight to view the plasma: 9 through the vertical port and 10 through the horizontal port. Each line is provided by a set of three detectors.

One of them is a CsI(Tl) scintillator coupled to a photodiode detector, which is used to measure the gamma-rays and the hard X-rays resulting from the fast electron bremsstrahlung, in a range from 200 keV to 6 MeV [8]. Since the noise is an intrinsic problem of PIN photodiodes (unitary gain), the

CsI(Tl)/photodiode detector is coupled to a low noise charge sensitive preamplifier with a gain of 10-15mV/MeV to keep the noise level as low as possible [9,10]. The ripple of the detector biasing supply and preamplifier power supply is also extremely important to obtain satisfactory results. Although the pulses obtained with this photodiode present an exponential shape, the former system uses a spectroscopy shaping amplifier that amplify and shape the signals to a Gaussian format prior to send it for the PHA instrumentation – a multichannel analyzer (MCA). The MCA accommodates the gamma-ray count rate in four energy windows. Both hard X-ray and gamma-ray could not be obtained simultaneously.

3.1. ATCA DIGITIZER SYSTEM

To have all range of pulses energy in the same spectrum, a new digitizer system was installed for both hard X-ray and gamma-ray diagnostics, replacing the former MCA. The system, ATCA based, is composed by an ATCA shelf, an ATCA controller and 5 ATCA digitizers [11]. Each digitizer is composed by 8 analog to digital converters (ADC) performing at a maximum of 250 Msamples/s, four GB of local memory (DDR2) and two Virtex-4 FPGAs. During preliminary tests in laboratory with a spare detector, it was concluded that with acceptable signal to noise ratio, the digitization of data directly from the detector is possible, avoiding the usage of the external analog shaper.

3.2. FPGA CODE

Each FPGA in the ATCA digitizers is physically connected to four ADCs and to two GB of DDR2. The FPGA is responsible for performing all the following basic tasks: all the data path, triggering and clocks management, storage in DDR2, and PCIe links to host. The FPGA is also responsible for the RT algorithms implementation.

Predicting the tests during commissioning and during next campaigns, a dedicated FPGA code that implements the two above described algorithms (sections 2.1 and 2.2), to be processed simultaneously, was developed. The algorithm for Gaussian shaped pulses must be selected when the analog shaper is between the detector and the digitizer system. For signals acquired directly from the detector, the algorithm based on trapezoidal filter must be used.

The algorithms choice is selectable by the user during discharge configuration. The scheme of the developed FPGA code with the two algorithms (Gaussian Proc. and Direct Proc. blocks) is presented in figure 3.

When the new digitizer system is directly connected to the detector/preamplifier, the RT algorithm can always be digitally improved and adjusted to the signal source. This feature is limited when an analog shaping amplifier is used, since it changes the signal source before being digitized, including rejecting important information such as the pileup. For that reason the direct acquisition from detector is the preferred setup. However, due to the poor resolution of the CsI(Tl)/photodiode detector, under severe plasma conditions or due to unfavorable signal conditions, the signal can be too embedded in noise and an external shaping amplifier may be required to externally increase the signal to noise ratio. This will confirm the signal validity, by using the algorithm for Gaussian pulses, and with this knowledge the digital algorithm for exponential signal can be improved, restoring the pulses embedded in noise.

Due to the larger pulses presented by the detector (rise time of 200 ns and pulse duration > 400us) performing at 50MHz is sufficient for these diagnostics. A Finite Impulse Response (FIR) decimator is implemented, allowing the acquisition at lower frequencies to a minimum of 5 Msamples/s. This will benefit from having fewer samples in each pulse, making the pulses with less resolution but more visually detectable.

4. RESULTS

JET is actually under shutdown which did not allow the test of the algorithms in real conditions with plasma. However, laboratory tests with the two algorithms were achieved in the FPGAs of the digitizer system, using a spare detector with radioactive sources (60Co, 137Cs and 22Na).

In figure 4 a spectrum obtained at JET with the RT algorithm for Gaussian shaped pulses is presented, using the 60Co and the 137Cs radioactive sources. This spectrum was achieved with data coming from the 670 ORTEC shaping amplifier settled with gain of 10 and shaping time of 10 us. The data was acquired at 5 Msamples/s.

In figure 5 a spectrum obtained at IST with the RT algorithm for exponential pulses is presented, using the 60Co radioactive source. The data of this spectrum was acquired at 50 Msamples/s directly from detector. According to trapezoidal filter parameters, the settled shaping time, was 14us.

The presented RT spectra were compared with spectra obtained by post-processing algorithms implemented in MATLAB, using raw data stored in the digitizers, and acquired in the same working conditions. The spectra are similar for both methods (RT and post-processing). The Full Width Half Maximum (FWHM) values obtained for photopeaks acquired in similar working conditions are presented in table 1.

CONCLUSIONS

The developed RT algorithms implemented in the FPGAs of the new digitizer system allow building in RT the spectra from the 19 lines of sight of the JET gamma-ray/hard X-ray profile monitor, in the energy range from 200keV to 6MeV. The algorithms were successfully tested with a spare detector and radioactive sources. When compared to post processing algorithms, RT processing return equivalent results with a deeply decrease on time consuming. The RT algorithms have to be validated during project commissioning in next JET campaigns.

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REFERENCES

[1]. Izuru Yonekawa, Data acquisition and management requirement for ITER, Fusion Engineering and Design **43** (1999) 321-325.

[2]. J. Sousa, et al., PCI data acquisition and signal processing hardware modules for long pulse operation, Review of Scientific Instruments **75** (2004) 4271-4273.

[3]. Cardoso J., Neto H., Compilation for FPGA-Based Reconfigurable Hardware, IEEE Design & Test, **20**(2) (2003) 65-75.

[4]. Jack L Parker, Instrumentation for Gamma-Ray Spectroscopy, in: Doug Reilly, Norbert Ensslin and Hastings Smith (Eds.), Passive Nondestructive Assay of Nuclear Materials, U.S. Nuclear Regulatory Commission, Washington, 1991, pp. 65-92.

[5]. ORTEC® 671 Spectroscopy Amplifier, www.ortec-online.com/download/671.pdf [online].

[6]. V.T. Jordanov et al, Digital techniques for real-time pulse shaping in radiation measurements, Nuclear Instruments and Methods in Physics Research Section A: 353 (1994) 261–264.

[7]. A.M. Fernandes, et al., Parallel Processing Method for High Speed Real Time Digital Pulse Processing for Gamma-Ray Spectroscopy, Fusion Engineering and Design, **85**(3-4) (2010) 308-312.

[8]. Kiptily V.G. et al., Gamma-ray imaging of D and ^{4}He ions accelerated by ion-cyclotron-resonance heating in JET plasmas, Nuclear Fusion **45** (2005) L21-L25.

[9]. P. Schotanus, Specifications Charge Photodiode Detectors JET, Scionix Holland Bv., 2009, Internal document.

[10]. http://www.scionix.nl/readout.htm [online].

[11]. R.C. Pereira, et al., ATCA data acquisition system for gamma ray spectrometry, Fusion Engineering and Design, **83** (2008) 341–345.

Source	**Photopeaks**	**FWHM RT algorithm**	**FWHM Post Processing algorithm**
137Cs	667keV	12,0 (fig.4)	13,6
60Co	1173keV	7,03 (fig.5)	7,48
	1331keV	7,39 (fig.5)	7,36

Table 1: FWHM of photopeaks from RT spectra and post processing spectra, built with data acquired under the same working conditions.

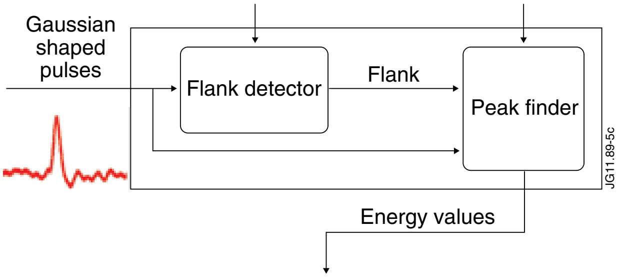

Figure 1: Schematic representation of the RT algorithm implemented at the FPGAs to determine the amplitude of Gaussian shaped pulses.

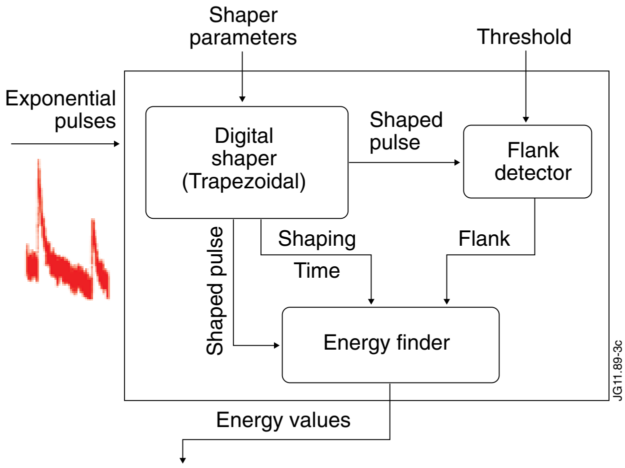

Figure 2: Schematic representation of the RT algorithm based on a trapezoidal shaper used to determine the amplitude of exponential pulses.

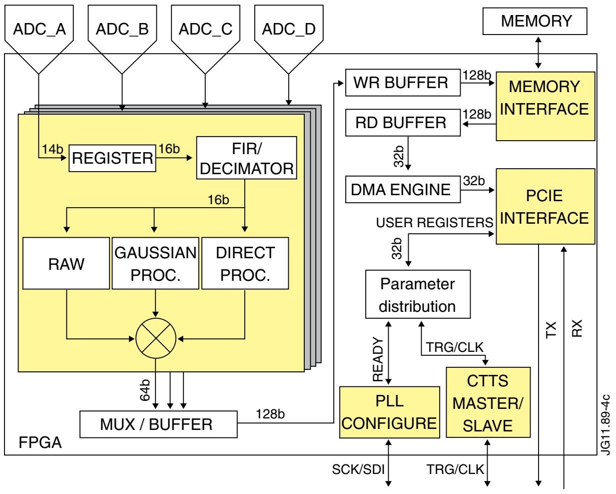

Figure 3: Scheme of the FPGA code of the digitizer system with the two algorithms (Gaussian Processing and Direct Processing) processing simultaneously.

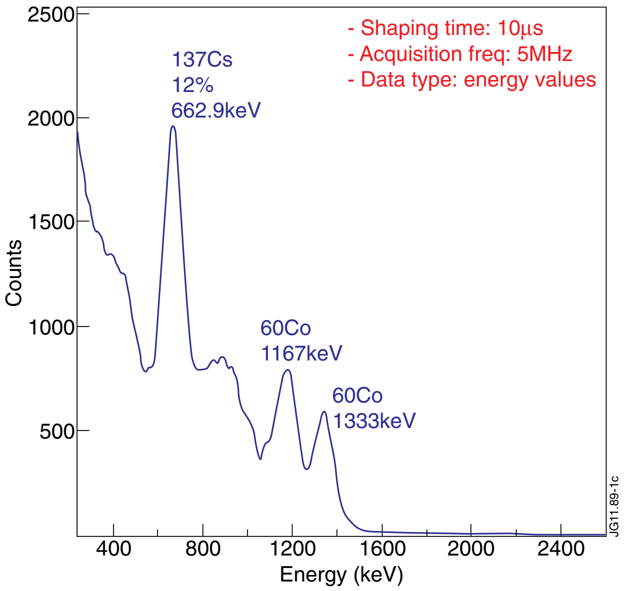

Figure 4: Spectrum obtained with the RT algorithm for Gaussian shaped pulses implemented in FPGA. An analog shaping amplifier (ORTEC 670) was used with gain x10 and 10 us of shaping time. Data acquired at 5 Msamples/s.

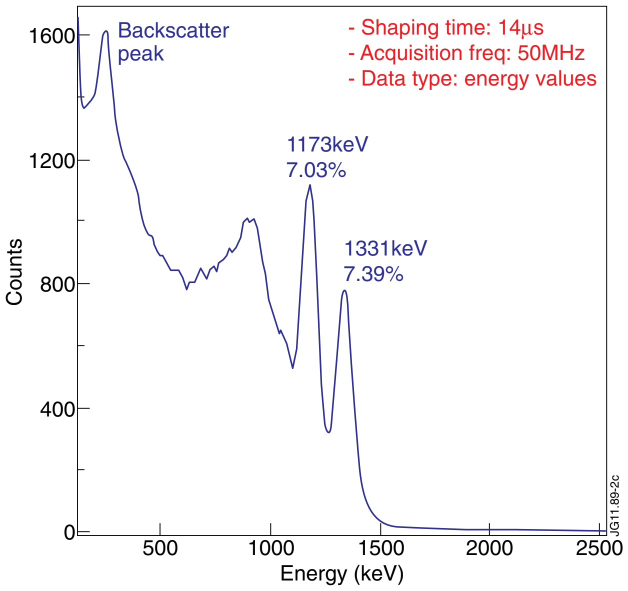

Figure 5: RT Spectrum obtained with algorithm for exponential signals implemented in FPGA. A shaping time of 14 us was used and data were acquired at 50 Msamples/s.