New FPGA processing code for JET gamma-ray camera upgrade

A. Fernandes[a], R.C. Pereira[a], B. Santos[a], J. Bielecki[b,c], G. Boltruczyk[d], A. Broslawski[d], P.F. Carvalho[a], J. Figueiredo[a,c], L. Giacomelli[d], M. Gosk[d], V. Kiptily[c], S. Korolczuk[d], A. Murari[c], M. Nocente[e,f], D. Rigamonti[e,f], J. Sousa[a], M. Tardocchi[f], A. Urban[d], I. Zychor[d], C.M.B.A. Correia[g], B. Gonçalves[a] and JET Contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[a]*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[b] *Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland*
[c] *Culham Centre for Fusion Energy, Culham, United Kingdom*
[d] *Narodowe Centrum Badań Jądrowych (NCBJ), 05-400 Otwock, Poland*
[e] *Dipartimento di Fisica "G. Occhialini", Università degli Studi di Milano-Bicocca, Milano, Italy*
[f] *Istituto di Fisica del Plasma "P. Caldirola", CNR, Milano, Italy*
[g] *LibPhys-UC, Department of Physics, University of Coimbra, P-3004 516 Coimbra, Portugal*

The Gamma Ray Camera Upgrade (GCU) project aims at installing a new set of 19 scintillators with multi-pixel photon counter (MPPC) embedded, capable to meet the high fluxes expected during deuterium-tritium plasmas while improving the diagnostic spectroscopic capabilities. GCU will benefit from the Advanced Telecommunications Computing Architecture (ATCA) based Data Acquisition System (DAQ), successfully installed and commissioned during the JET-EP2 enhancement. However, to cope with the new GCU detector signals, the DAQ Field Programmable Gate Array (FPGA) codes need to be rebuilt. This work presents the FPGA code upgrade for DAQ gamma camera, capable to sustain the expected fast response of new detectors, while exploiting the full capabilities of the DAQ. Dedicated codes were designed, capable to acquire the new signals at full rate, and simultaneously processing it in real-time through suitable algorithms, fitted to the new signal shape. First results of real-time processing codes applied to data from detector prototypes are presented.

Keywords: ATCA, FPGA, Real-Time Processing, Gamma-ray Spectroscopy, Nuclear Fusion.

1. Introduction

The 2D Gamma-ray Camera of the Joint European Torus (JET) is one of the target diagnostics for physics exploitation during next high-power Deuterium-Tritium (DT) experiments [1]. From the gamma-ray emission spectra, associated with specific reactions among fast ions and fusion alphas with impurities, it will be possible to infer information on the spatial distribution of these fast ions and alpha particles, and to follow their evolution in time [1].

The Gamma-ray Camera Upgrade (GCU) project aims to improve the spectroscopic properties of the existing gamma camera in terms of energy resolution and high counting rate capability, allowing its operation during DT experiments [2, 3]. New 19 $LaBr_3$ based detectors were installed during 2017 shutdown, featuring an energy resolution of 5% (Energy Resolution = FWHM/En) at 1.1 MeV and count rate capability in excess of 500 kHz [3, 4, 5].

The GCU Data Acquisition (DAQ) system, an Advanced Telecommunications Computing Architecture (ATCA) based DAQ successfully installed and commissioned during the JET-EP2 enhancement [6], aims to acquire and simultaneously process the new 19 GCU detector signals. Dedicated algorithms for DAQ Field Programmable Gate Arrays (FPGAs) are being developed, capable of real-time processing the incoming signals, delivering only the energy value of founded events and its corresponding time occurrence. During past experiments the DAQ was operating at a down-sampling rate of 2.5 Msamples/s, coping with the long pulse length of former CsI(Tl) based detectors [6]. As so, the new algorithms are needed to properly process the new fast signals at full DAQ rate, as described in next sections.

2. GCU DAQ

The GCU DAQ system is composed by an ATCA shelf with 3 digitizer modules connected to a controller through PCI-express (PCIe) links [7]. Each ATCA digitizer module is composed by eight Analog to Digital Converters (ADC) with a maximum sampling rate of 250 Msamples/s, 2 GB of local memory (DDR2) and two Virtex-4 FPGAs [8]. Besides the basic module functionalities, the true parallelism of FPGAs make them suitable for real-time processing and data reduction. Four data management operation modes were designed for

author's email: anaf@ipfn.tecnico.ulisboa.pt

**See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)*

GCU FPGAs: (i) raw data – all acquired samples are stored in local memory; (ii) pulse storage - occurrences above a predefined threshold are stored; (iii) processing - perform real time algorithms storing only the energy of the events with its corresponding time stamp; (iv) filter – when a processing filter is present (e.g. trapezoidal shaper [9]), this option stores filtered data for calibration and debug. For all modes, stored data is sent through DMA packets to host when the acquisition finishes.

From the maximum count rate expected during DT (500kevents/channel) [3, 4], and according with the total digitizer memory available per ADC channel (500 MB) for each JET discharge, it was concluded, as depicted in table 1, that real-time processing is needed for data storage without losses at those rates. Furthermore, this was the default mode of past experiments, allowing proper inter-shot pulse analyses of all 19 CsI(Tl) signals during experiments.

Table 1. Memory requested per channel for a single discharge.

	Count Rate (kevent/s)	Samples /event*	Time @ max count rate (s)	Mem. /channel (MB)
Pulse storage	500	64	10	680
	500	128	10	1320
RT process	500	4	10	**80**
	1000	4	30	**480**

*1 sample = 2-Byte

According with figs. 1 and 2, events from $LaBr_3$ based detector (fig. 1) present a much shorter pulse length and a slightly different shape, when compared with former CsI(Tl) signals (fig. 2).

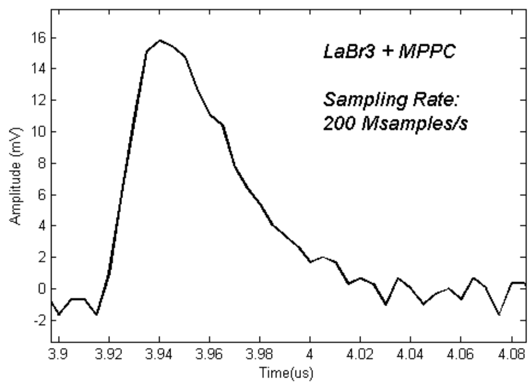

Fig. 1. Pulse from $LaBr_3$, after its installation in gamma camera, at lab, during shutdown (according with past experience, additional noise is foreseen with camera in place during experiments).

The events from former CsI(Tl) based detectors (fig.2), in operation until end of 2016, presented pulse lengths >400 us, and shape similar to ramp-like pulses. Dedicated algorithms were implemented at FPGA in other to properly process these type of signals [10].

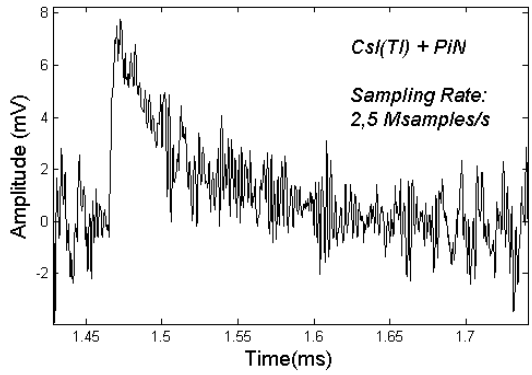

Fig. 2. Pulse from CsI(Tl) based detectors, with cameras in place during experiments.

In opposite, $LaBr_3$ based detectors deliver short pulses with sharp peaks and fast decay (~120 ns pulse length), similar to exponentials (fig.1). As so, new algorithms were identified and implemented at GCU FPGAs, capable to correctly process the fast $LaBr_3$ incoming signals.

3. Real-time processing code

Different methods can be used for real-time processing GCU detector signals. Foreseeing its portability to an FPGA environment, three algorithms were selected and tested: i) Pulse Height Analysis (PHA) – the pulses amplitude is proportional to the energy of the corresponding events interacting in the detector; ii) Digital Trapezoidal Shaper (DTS) – exponential signals are transformed into trapezoids, whose amplitude is proportional to the energy of the events; Charge Integration (CI) – The pulse area is proportional to the energy of the events.

Tests were made by post-processing the data, from a detector prototype in presence of high rates (up to 1,5 Mevents/s), acquired at TANDEM-ALPI accelerator of the Legnaro National Laboratories. Expected spectra with multi gamma lines can be observed with that data, from reactions between 10 MeV proton and a ^{27}Al target placed in a cylindrical vacuum chamber [3, 5].

Taking into account the rates expected during DT, it was concluded that the CI method presents the highest dependence on count rate, with special spectra degradation at high rates. In opposite, both PHA and DTS algorithms are able to produce expected spectra even at high count rates (1,5 Mevents/s), with improved peaks resolution when DTS method is applied. The latest, considered as a quasi-optimum filter capable of suppressing ballistic deficit of sharp exponential pulses [9], is being widely used at improved spectroscopy analyses. As so, DTS is considered so far the most adequate method for real-time processing the GCU data. However, this method requires adjustments on filter parameters, dependent on signal shape and noise, as so less immediate than PHA. The PHA is considered the fastest method. It can easily determine the energy of the pulses, very useful for fast results during test phases (e.g. detectors installation; first tests when camera in place).

Both PHA and DTS based algorithms were implemented in GCU FPGAs. Taking into account the expected pile-up during DT, the DTS parameters were slightly modified. As depicted in figure 3, filtered signals are similar to a Gaussians instead of pure trapezoids.

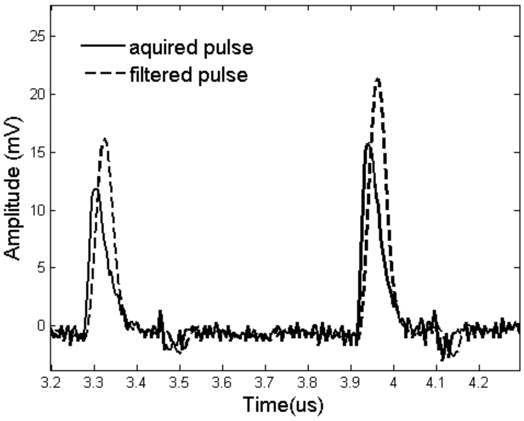

Fig. 3. Raw data pulses and filtered pulses based on DTS.

4. Results

The two real-time methods, PHA and DTS, were successfully implemented and tested with prototype detectors. First results were obtained from the PHA method applied to the prototype detector (first version) installed in channel #10 of gamma camera during 2016 experiments. In figure 4 is depicted the time trace (counts/time) obtained for discharge #91975, highlighting the interval when the two heating systems, the neutral beam injector (NBI) and the Ion cyclotron resonance heating (ICRH), were launched.

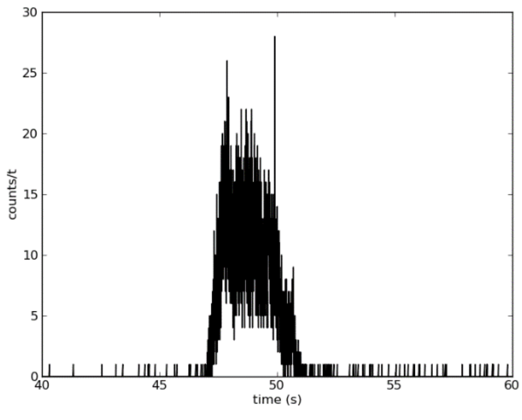

Fig. 4. Time trace of detector #10 in horizontal camera (first version of GCU prototype detectors) during discharge #91975. It was obtained from real-time data processed at FPGA using the PHA method.

For the detectors installation phase (final version), both horizontal and vertical cameras were temporally placed at laboratory, near diagnostic cubicle. Single acquisition were made for all detectors, through a long cable (~10 m) connecting each detector to an ATCA ADC channel. Were made short (120 s) and long (up to 6 h) acquisitions, in presence of ^{22}Na and ^{137}Cs radioactive sources. Due to security reasons, it was not allowed to use stronger sources with high energy peaks.

During the installation tests the DTS method was also used, being possible to produce suitable spectra for all 19 channels with this improved solution. As example, figure 3 depicts a spectrum of data from channel 10, produced with DTS method at FPGA, for 6 hours acquisition, in presence of ^{22}Na radioactive source (week source - ~ 14 events/s - embedded in detectors set). Figure 4 presents a spectrum of data produced with the same method, from the same detector, for 3 minutes acquisition, in presence of ^{137}Cs radioactive source (high activity source ~ 1.8 kevents/s).

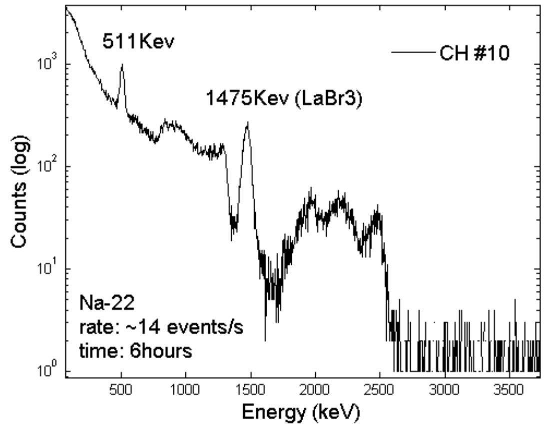

Fig. 5. Spectrum of channel 10, for 6 hours acquisition using the DTS method at FPGA, in presence of ^{22}Na radioactive source (week source - ~ 14events/s - embedded in detectors set).

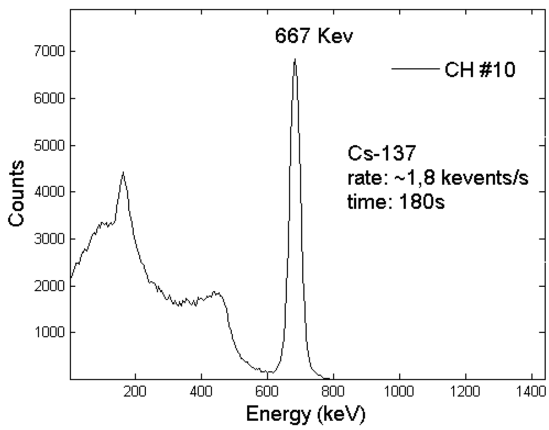

Fig. 6. Spectrum of channel 10 for 3 minutes acquisition using the real-time DTS algorithm at FPGA, in presence of ^{137}Cs radioactive source (~1.8 kevents/s).

Similar spectra were observed for all 19 channels, as expected. Concerning the acquisitions in presence of ^{137}Cs source, it was achieved an energy resolution (FWHM/E) between 4.7% and 5.7% for the 667 keV peak, depending on the detector, which is in agreement with detector datasheets [11].

Moreover, real-time spectra were validated with spectra obtained from post-processing methods using event based data, as well as with spectra produced with a CAEN DTS5730 portable digitizer card [12].

5. Conclusions

This paper presents the first results obtained with two selected algorithms implemented at FPGA, the PHA and the DTS based methods, capable of real time processing the fast incoming signals of new GCU $LaBr_3$ based detectors. While the DTS based algorithm provides improved resolution for the new incoming signals, considered so far the most adequate method to process the GCU data in real time, the PHA is considered the best option to obtain fast results, very useful during test phases. Nevertheless, for final validation further tests are needed, with both horizontal and vertical cameras in place, as well as with plasma. According with past experiments, it is expected an intrinsic noise associated with the long cabling as well as some interference from other systems during JET operation. Moreover, it is known that spectra resolution starts substantially declining when the counting rate increases to a level that the percentage of superimposed pulses becomes essential [13]. Nevertheless, benefiting from the reconfigurable feature of GCU DAQ, FPGA code can always be updated if needed (e.g. improved filtering [10]; advanced pileup resolving methods [14, 15]) without compromising the diagnostic availability.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.

IST activities also received financial support from "Fundação para a Ciência e Tecnologia" through project UID/FIS/50010/2013. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] V.G. Kiptily, et al., "Fusion Alpha-Particle Diagnostics for DT Experiments on the Joint European Torus", AIP Conf. Proc. 1612 , 87 (2014).

[2] I Zychor, et al., "High performance detectors for upgraded gamma ray diagnostics for JET DT campaigns", Physica Scripta vol 91, 064003 (2016).

[3] D. Rigamonti, A. Muraro, M. Nocente, V. Perseo, G. Boltruczyk, A. Fernandes, J. Figueiredo, L. Giacomelli, G. Gorini, M. Gosk, V. Kiptily, S. Korolczuk, S. Mianowski, A. Murari, R. C. Pereira, E. P. Cippo, I. Zychor, M. Tardocchi, and JET Contributors, Performance of the prototype LaBr3 spectrometer developed for the JET gamma-ray camera upgrade, Review of Scientific Instruments 87, 11E717 (2016).

[4] G. Boltruczyk, A. Broslawski, M. Gosk, S. Korolczuk, R. Kwiatkowski, M. Linczuk, A. Urban, J. Bielecki, R. Costa Pereira, A. Fernandes, J. Figueiredo, V. Kiptily, A. Murari, M. Nocente, V. Perseo, D. Rigamonti, B. Santos, M. Tardocchi, I. Zychor, JET contributors, Development of MPPC-based detectors for high count rate DT campaigns at JET, Fusion Eng. Design, (2017).

[5] M. Nocente, D. Rigamonti, V. Perseo, M. Tardocchi, G. Boltruczyk, A. Broslawski, A. Cremona, G. Croci, M. Gosk, V. Kiptily, S. Korolczuk, M. Mazzocco, A. Muraro, E. Strano, I. Zychor, and G. Gorini, Review of Scientific Instruments 87, 11E714 (2016).

[6] A.M. Fernandes, R.C. Pereira, A. Neto, D.F. Valcárcel, D. Alves, J. Sousa, B.B. Carvalho, V. Kiptily, B. Syme, P. Blanchard, A. Murari, C.M.B.A. Correia, C.A.F. Varandas, Bruno Gonçalves, and JET-EFDA Contributors, "Real-Time Processing System for the JET Hard X-Ray and Gamma-Ray Profile Monitor Enhancement", IEEE Transactions on Nuclear Science, vol 61 (3), pp. 1209-1215, June 2014.

[7] A. J. N. Batista, J. Sousa, and C. A. F. Varandas, "ATCA digital controller hardware for vertical stabilization of plasmas in Tokamaks, "Rev. Scientif. Instrum., vol. 77, p. 10F527, 2006.

[8] R. C. Pereira, A. M. Fernandes, A. Neto, J. Sousa, A. J. Batista, B. B.Carvalho, C. M. B. A. Correia, and C. A. F. Varandas, and JET-EFDA contributors, "ATCA fast data acquisition & processing system for JET gamma-ray cameras upgrade diagnostic," IEEE Trans. Nucl. Sci., vol. 57, no. 2, pp. 683–687, Apr. 2010.

[9] V.T. Jordanov, G.F. Knoll, A.C. Huber, J.A. Pantazis, Digital techniques for real-time pulse shaping in radiation measurements, Nucl. Instrum. Methods Phys. Res. A: Accelerators, Spectrometers, Detectors and Associated Equipment 353 (1–3) pp. 261–264 (1994).

[10] A. Fernandes, R.C. Pereira, D.F. Valcárcel, D. Alves, B.B. Carvalho, J. Sousa, V. Kiptily, C.M.B.A. Correia, B.Gonçalves, JET-EFDA Contributors, "Real-time algorithms for JET hard X-ray and gamma-ray profile monitor", Fusion Engineering and Design - Special issue on real-time systems in fusion, vol. 89 (3), pp. 259-266, March.2014.

[11] GCU_D20_2017_NCBJ.pdf (internal report), Report on M25: Detector assembly and laboratory tests with radioactive source and C&M, National Centre for Nuclear Research, Swierk, Poland, (2017).

[12] CAEN (2017, May 29), DT5730. Retrieved from http://www.caen.it/csite/CaenProd.jsp?parent=14&idmod=757#.

[13] M. Nocente, M. Tardocchi, A. Olariu, S. Olariu, R. C. Pereira, I. N. Chugunov, A. Fernandes, D. B. Gin, G. Grosso, V. G. Kiptily, A. Neto, A. E. Shevelev, M. Silva, J. Sousa, and G. Gorini "High Resolution Gamma Ray Spectroscopy at MHz Counting Rates With LaBr Scintillators for Fusion Plasma Applications", IEEE Transactions on Nuclear Science, vol 60 (2), pp. 1408-1415, April 2013.

[14] Kiptily V.G., Chugunov I.N., Gin D.B., Shevelev A.E., Heesterman P.J.L. and Murari A. 2006 Advanced data acquisition system for gamma-ray spectrometry in JET, 33rd EPS Conf. on Plasma Physics, vol 301 (ECA) P-1.077.

[15] D.B. Gin, I.N. Chugunov, A.E. Shevelev, Instrum. Exp. Tech. 51 (2) (2008) 240.