Fusion Engineering and Design 89 (2014) 259–266

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Real-time algorithms for JET hard X-ray and gamma-ray profile monitor

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HIGHLIGHTS

- Real-time tools and mechanisms are required for data handling and machine control.
- A new DAQ system, ATCA based, with embedded FPGAs, was installed at JET.
- Different real-time algorithms were developed for FPGAs and MARTe application.
- MARTe provides the interface to CODAS and to the JET real-time network.
- The new DAQ system is capable to process and deliver data in real-time.

ARTICLE INFO

Article history:
Received 28 March 2013
Received in revised form 1 July 2013
Accepted 5 August 2013
Available online 10 September 2013

Keywords:
FPGA
Digital pulse processing
Real-time processing
ATCA
MARTe

ABSTRACT

The steady state operation with high energy content foreseen for future generation of fusion devices will necessarily demand dedicated real-time tools and mechanisms for data handling and machine control. Consequently, the real-time systems for those devices should be carefully selected and their capabilities previously established. The Joint European Torus (JET) is undertaking an enhancement program, which includes tests of relevant real-time tools for the International Thermonuclear Experimental Reactor (ITER), a key experiment for future fusion devices. In these enhancements a new Data AcQuisition (DAQ) system is included, with real-time processing capabilities, for the JET hard X-ray and gamma-ray profile monitor. The DAQ system is composed of dedicated digitizer modules with embedded Field Programmable Gate Array (FPGA) devices. The interface between the DAQ system, the JET control and data acquisition system and the JET real-time data network is provided by the Multithreaded Application Real-Time executor (MARTe). This paper describes the real-time algorithms, developed for both digitizers' FPGAs and MARTe application, capable of meeting the DAQ real-time requirements. The new DAQ system, including the embedded real-time features, was commissioned during the 2012 experiments. Results achieved with these real-time algorithms during experiments are presented.

1. Introduction

The recent availability of ultra-high frequency (GB/s) Data AcQuisition modules (DAQ) necessarily increase the needs of dedicated real-time tools for a wide range of applications [1]. These modules are able to produce large amounts of data thus leading to storage problems. Real-time tools and algorithms are also required by the expected steady state operation of next fusion devices. In continuous operation it is unfeasible to store all the data only after the end of the discharge for posterior processing and analysis [2]. Accordingly, real-time mechanisms (e.g. real-time processing; intelligent triggering systems for events storage) must guarantee the storage of useful information during all the discharge.

The Joint European Torus (JET) is undertaking an enhancement program where real-time tools and mechanisms for data-handling and machine control are being tested. These enhancements include a new DAQ system, based on Advanced Telecommunication Computer Architecture (ATCA®), for digitizing the hard X-ray and gamma-ray signals detected by the 19 Fast Electron Bremsstrahlung (FEB) detectors (CsI(Tl) scintillators coupled to photodiodes) of the JET profile monitoring system [3]. This ATCA-based DAQ system, developed at Instituto de Plasmas e Fusão

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http://dx.doi.org/10.1016/j.fusengdes.2013.08.002

Nuclear, was expected to overcome some of the former FEB diagnostic limitations in the acquisition system and simultaneously exploit required real-time features [4]. ATCA has been extensively used for control and data acquisition systems for fusion experiments [5]. Moreover, ATCA-based control and data acquisition are also being considered for the International Thermonuclear Experimental Reactor (ITER) fast plant system controller, an extensive prototyping program whose specification will be applicable to several diagnostic systems targeting plasma control [6].

The DAQ system installed at JET is composed of a commercial ATCA shelf, an ATCA controller [7] with an Intel® Core™ 2 Duo ×86 processor, three fast digitizer modules [8] to cover all the 19 channels, and a commercial Peripheral Component Interconnect (PCI)/Asynchronous Transfer Mode (ATM) module. Each digitizer module is composed of eight 13-bit resolution Analog to Digital Converters (ADCs) with a sampling rate up to 250 MSamples/s, 4GB DDR2 SODIMM local memory, and two Field Programmable Gate Array (FPGA) devices from Xilinx (XC4VFX60/1152). Besides the basic module functionalities, FPGAs are used for real-time data reduction and pulse processing, being capable of delivering in real-time the energy of the pulses acquired from the 19 FEB detectors. The PCI/ATM module is mandatory for connecting to the JET real-time data network, an ATM network for the real-time interchange of data between diagnostics and control systems, foreseeing control purposes [4]. The interface to the JET control and data acquisition system, and to the JET real-time data network, is provided by the Multithreaded Application Real-Time executor (MARTe) [9], a C++framework used in several fusion machines and installed at the ATCA controller. The MARTe-based application is running under the Linux® OS with the kernel version 2.6.35.9. To cope with the DAQ real-time requirements, and foreseeing new real-time applications, several real-time algorithms were developed, implemented and tested in the DAQ system. They can be divided in: (i) algorithms for digitizers' FPGAs and (ii) algorithms for MARTe application. The developed algorithms are described in Sections 2 and 3, highlighting that some of them are not currently being used by the new hard X-ray and gamma-ray profile monitor diagnostic. The achieved results are presented in Section 4, followed by the conclusions.

2. Real-time algorithms for FPGA

FPGAs have become increasingly used for real time algorithm processing and data transfer in instrumentation modules, due to their: (i) inherent parallelism of logic resources; (ii) flexibility in their configuration and (iii) unique performance at high frequencies [10]. With a suitable processing algorithm running in the FPGA it is possible to extract in real-time only the key information, leading to a significant data reduction. The FPGA algorithms are easily upgraded (e.g. due to signal changes after replacing detectors), ensuring a correct real-time analysis. Moreover, the FPGA is capable of processing different algorithms simultaneously which can be advantageous for some applications [11].

Different real-time processing algorithms, developed for the digitizer modules' FPGAs, were used for testing the DAQ system, firstly in laboratory, then in situ with radioactive sources, and finally with plasma during JET experiments. Furthermore, the different algorithms were required to accomplish with two distinct hardware setups (with and without a shaping amplifier in the signal path), deployed during the phase tests. These FPGA algorithms are presented in the following subsections. For their validation, the real-time processed data from the FPGA was compared with data from post-processing algorithms developed in MATLAB. The post-processing algorithms were applied to raw data acquired in the same working conditions.

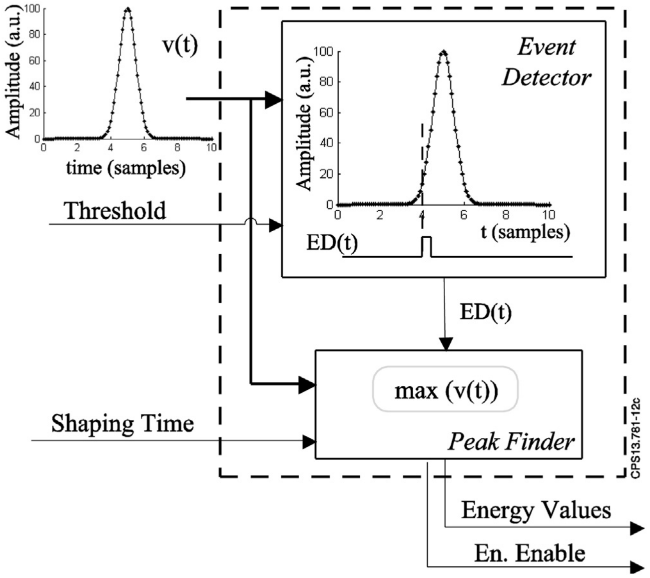

Fig. 1. Schematic representation of the real-time algorithm implemented at FPGAs for each channel (dashed rectangle) to determine the amplitude of Gaussian shaped pulses. The algorithm receives the acquired signal ($v(t)$), the threshold and the shaping time. It returns the energy values of the acquired pulses, signaled by the Energy Enable bit. *Legend*: ED, event detector.

2.1. Algorithm for Gaussian shaped pulses

A real-time algorithm was developed and implemented at the digitizer modules' FPGAs in order to calculate the amplitude of Gaussian shaped pulses, obtained when an external shaping amplifier is placed between the detectors and the digitizers. Considering that the pulses amplitude is proportional to the energy of the corresponding photon that interacts in the detector, every time a threshold is reached in the acquired signal the algorithm starts to find the maximum amplitude, as depicted schematically in Fig. 1. If no other maximum occurs during the expected pulse duration, defined by the settled shaping time, the achieved maximum value is stored with the corresponding time-stamp, in a 64-bit word.

A shaping amplifier is commonly used for improving the Signal to Noise Ratio (SNR), for baseline restoring, and for rejecting pileup [12]. However, its presence in the signal path changes the signal source before being digitized, and rejects important information that can be treated digitally (e.g. pileup). Consequently, the direct connection is a preferable setup, mainly when fast digitizer modules are used. However, it became evident while testing that, due to the poor SNR of the FEB detectors, it was of crucial importance having external shaping amplifiers in the signal path, the same setup used by the former DAQ system [11]. This setup allowed to emphasize the incoming pulses, and the algorithm applied to Gaussian shaped pulses was used to attest that the pulses could be detected. The algorithm was important to conclude that the maximum ADC sampling rate (250 MHz) was too high for sampling the incoming signals. The effective number of bits increases if the signal is down-sampled and, consequently, the pulses with less resolution become more visible [11].

2.2. Algorithm for ramp-like pulses

If the signals from the detectors are directly connected to the digitizer modules' ADCs, all data processing functions, such as filtering and shaping, baseline restoration, ballistic deficit correction, and pileup reject/resolving, need to be executed digitally [13]. A common pulse shape returned by gamma-ray/X-ray spectroscopy detectors is similar to an exponential signal with a fast positive