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# Hardware architecture of the data acquisition and processing system for the JET Neutron Camera Upgrade (NCU) project

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The Neutron Camera (NC) is a Joint European Torus (JET) diagnostic, based on a set of 19 collimated lines of sight equipped with plastic (BC418) and liquid (NE213) scintillators, with the main function of measuring the neutron emissivity profile due to 2.5 MeV (DD) and 14 MeV (DT). Due to several limitations of the present data acquisition system and in view of the JET DT campaign, an enhancement project (Neuron Camera Upgrade, NCU) was launched. The main objective was to improve the measurement capability of NC for 14 MeV neutrons, by application of a high throughput FPGA-based digital acquisition system. The present paper describes the hardware architecture and the FPGA processing selected for the NCU project and the first tests carried out at JET.

Keywords: FPGA; neutron detectors; digital processing; spectroscopy

## 1. Introduction

The JET NC diagnostic has the main function of measuring the neutron emissivity profile due to 2.5 MeV (DD) and 14 MeV (DT) neutrons over a poloidal plasma cross-section using line-integrated measurements along a number of collimated channels (lines-of-sight, LOS). The diagnostic consists of two separate shielding concrete units, each one including a fan-shaped array of collimators. One unit views the plasma horizontally (10 LOS), and the other vertically (9 LOS). Neutron measurements are performed by means of two different types of detectors: NE213 liquid scintillators (designed to work in DD operations and low power DT operations) and Bicron BC418 plastic scintillators (designed for high power DT operations and for the detection of low intensity DT neutrons in the presence of strong DD neutron fluxes). During the 1997 DTE1 campaign (record discharge #42976; maximum neutron yield ~ 6 $\times 10^{18}$ n/s$^{-1}$) the BC418 detectors worked up to ~1.2 $\times 10^6$ cps (counts above 10 MeV threshold, i.e. ~4.2 $10^6$ cps total count rate). The presence of higher NBI power in future DT campaigns might imply higher rates and a demanding value of ~2 $\times 10^6$ cps (counts above 10 MeV threshold, i.e. ~7 $\times 10^6$ cps total count rate ) has been set as a target for the diagnostic.

The BC418 detectors still work with an analogue acquisition electronics having several limitations [1]:

- No raw data (i.e. scintillator pulses) storage for monitoring and reprocessing purposes.
- No provision of accurate Pulse Height Spectra (PHS) during plasma discharges (analog discriminator modules provide counts in 4 energy bands only).
- Complex calibration procedure.

The NE213 detectors are instead coupled to a Field Programmable Gated Array (FPGA)-based digital acquisition system (14 bit ADC @ 200 MS/s sampling rate, PCIe×1 bus) developed by ENEA [2]. Such system overcomes the limitations listed above for the BC418 analogue acquisition chain but processing is limited to ~ 9 $\times 10^5$ cps in the lab [3].

To address the above mentioned limitations and in view of future JET DT campaigns, an upgrade project (Neuron Camera Upgrade, NCU) was launched in the frame of work-package JET4 (JET enhancements) with the main objective of increasing the performance and reliability of the 14 MeV neutron measurements performed by BC418 detectors. Such objective will be achieved by procuring, setting up, installing at JET and calibrating a new FPGA-based digital data acquisition system, which will include the following features:

- High throughput digital acquisition for each BC418 detector performing on-line data pre-processing.
- Raw data (i.e. scintillator pulses) mass storage on local computers located in the NC cubicles area.
- Off-line data processing (pile-up processing, DT neutron count rates, PHS, calibration, etc.) with dedicated software package running on the JET environment and on the local computers.

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A possible replacement of the NE213 acquisition system with the same presented in this paper for BC418 detectors is also foreseen. The decision will be taken after 14 MeV neutrons irradiation tests at high rate to be carried out at the Frascati Neutron Generator (FNG).

## 2. Hardware architecture

The hardware architecture selected for the NCU acquisition system is based on a set 5U-rack units (figure 1). Each unit is equipped with a 4-slots backplane (figure 2) hosting up to 4 PC boards (SBS - i7 3.4 GHz Ivy Bridge, (figure 3)) and each PC board accommodates a two-channel digitizer through a PCIex8 carrier board. Two rack units with all backplane slots occupied (16 acquisition channels) and one rack unit with 2 backplane slots occupied (4 acquisition channels) are used to provide full coverage of NC lines of sight and a spare acquisition channel.

The 10 two-channel digitizers (X6-400M, produced by the Innovative integration company ([4]) are equipped with a Xilinx$^{TM}$ Virtex 6 FPGA, 4 GBytes of Low Power Double Data Rate Memory (LPDDR2), two 1 GS/s DAC, external clock and trigger; each digitizing channel features a 14 bit ADCs with software selectable sampling rate up to 400MS/s. The FPGA board is mounted on the PCIex8 carrier as a high speed Switch Mezzanine Card (XMC) module, shown in figure 4.

Fig. 1. 5U rack unit containing four acquisition systems.

Fig. 2. 4 slot backplane, hosting the acquisition and processing units.

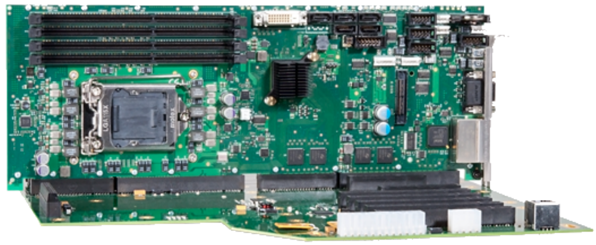

Fig. 3. PC board SBS- i7 3.4 GHz Ivy Bridge .

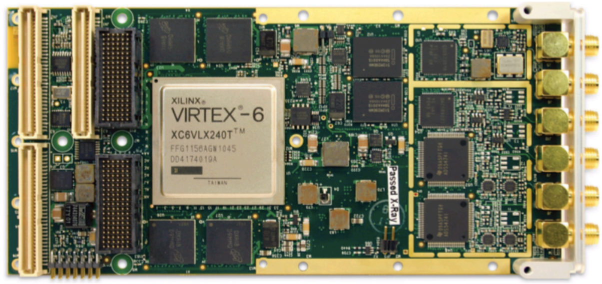


Fig. 4. X6-400M XMC mezzanine Card.

Some specific design choices were made in order to cope with the high data throughput foreseen in future DT campaigns:

- Large on-board RAM (4GBytes) and use of a fast bus for FPGA data buffering and data transfer (PCIex8, > 1GB/s)
- Maximization of processing resources per acquisition channel. Single FPGAs and PCs are allocated for each couple of acquisition channels, thus provide the system with robustness both against data overload on the FPGA/CPU and acquisition board/PC failure. A second PCIex8 slot is anyway available on the PC boards, allowing 2 additional acquisition channels to be installed.
- Sampling rate flexibility. The possibility of downgrading via software the 400Ms/s maximum sampling rate allows, depending on the need, to easily select between high performances (in terms of energy resolution, pile-up analysis and, in case of use with NE213 detectors, n/$\gamma$ separation) and data reduction.

It is also to be mentioned that the acquisition board supplier provided full access to FPGAs, thus allowing the use of the custom firmware specifically designed in ENEA for pulse acquisition and pre-processing [5]. The firmware takes advantage of a non-continuous acquisition policy in which a selectable number of samples (data window) are acquired when a pulse is detected and the size of the window is dynamically extended depending on the presence of additional pulses; such a procedure reduces the amount of stored data and increases the maximum count rate sustainable by the system.

A layout of the overall system, as it will be installed at JET, is shown in figure 5. Each detector signal passes through a fast amplifier and is then split in two paths, the first going to the digital system and the other to the old analogue system. Nonetheless, the possibility to split the detector signal before the amplifiers is also being investigated. JET reference CLOCK/GATE signals and network will be routed to each acquisition board/PC by means of dedicated distribution units. A 10 channels Keyboard Video and mouse (KVM) system will allow local access to PCs for set-up, monitoring and calibration purposes. Acquisitions will be synchronously triggered on all units by the JET PRE signal, active on the pulse start; scintillator pulses data will be stored in PCs RAM memory during plasma discharges and saved in the JET database as raw signals immediately after the end of the discharge. Processing of raw data will take place on the JET 'chain1' computer system (responsible for generating processed physics and engineering data after JET pulses) by means of a dedicated C++ code, providing PHS and 14 MeV neutron count rates for the different NC LOS. Local processing of raw data on NC PCs in the cubicles will be also possible for optimization purposes.

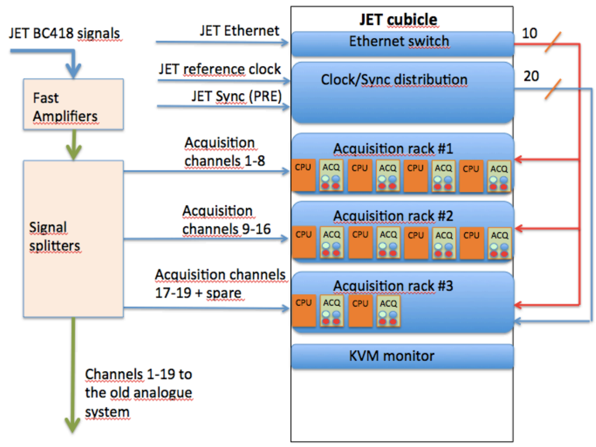


Fig. 5. Neutron Camera Upgrade: overall system architecture

## 3. JET tests

A portable acquisition system based on a X6-400M board has been used for a set of preliminary tests performed at JET. To verify the adequacy of the ADCs input range (1.1 V) when using default HV settings for the BC418 detectors, all NC channels have been energy calibrated by means of the Na22 gamma sources embedded in the NC detector boxes and the relation between neutron energy and ADC channels has been determined. Gamma calibration data were processed using the pulse peak to determine the pulse energy, so that the channels of the gamma pulse height spectra can be directly related to ADC channels. Figures 6a and 6b show the energy calibrated (electron equivalent energy, $E_{ee}$) PHS respectively for the horizontal and the vertical camera channels.

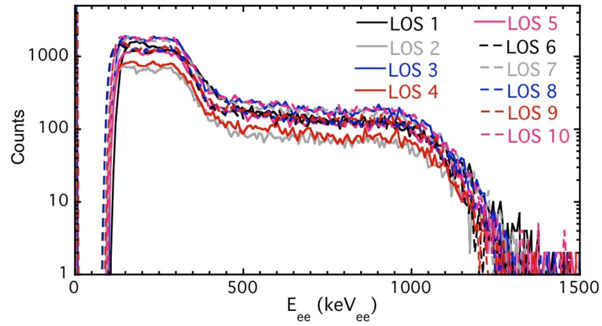


Fig. 6a. Energy calibrated Na22 PHS for the horizontal JET neutron camera.

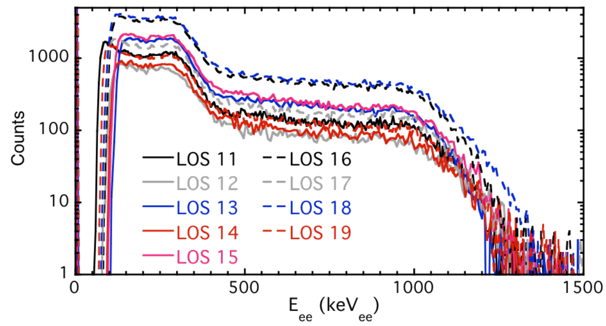


Fig. 6b. Energy calibrated Na22 PHS for the vertical JET neutron camera.

The neutron energy (E) vs. ADC channel curves deduced from gamma calibration are depicted in figures 7a and 7b. Conversion from electron equivalent energy to neutron energy (E) was made according to reference [6,7,8], i.e. using the formula:

$$E_{ee}(MeV) = a_1\left[1-\exp\left(-a_2E^{a_3}(MeV)\right)\right] + a_4E(MeV) \qquad (1)$$

$$a_1 = -8;\ a_2 = 0.1;\ a_3 = 0.9;\ a_4 = 0.95$$

Results indicate that the ADCs input range is adequate to enable 14 MeV detection. For some NC channels (especially for the vertical camera) the maximum detectable neutron energy is anyway close to 14 MeV; moreover PMT gain variations due to high count rate could further reduce such maximum detectable energy. Therefore, the use of resistive attenuators may be needed in order to reduce the amplitude of the pulses in input to the acquisition system.

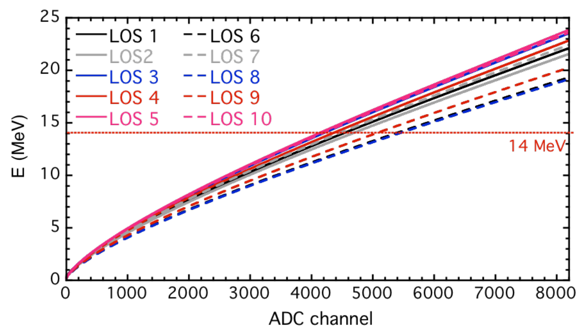


Fig. 7a. E Vs. ADC channel plot for the horizontal JET neutron cameras

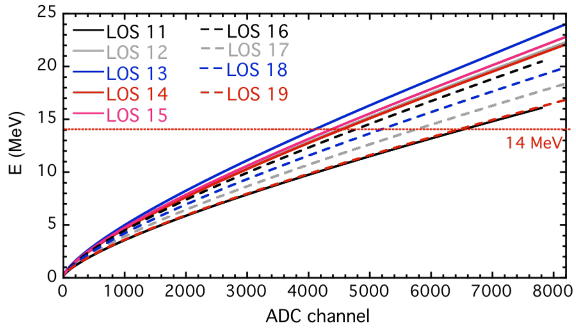


Fig. 7b. E Vs. ADC channel plot for the vertical JET neutron cameras

As a test on sampling rate requirements pulses from $^{22}$Na sources were acquired at 400 Ms/s and 250 Ms/s (figure 8). A slight reduction in pulse height resolution is observed which does not translate into a relevant change in the calculated position of the Compton edges (i.e. in the calibration lines) and therefore into a significant change in the position of the 10 MeV threshold normally used for or DT counting; 250 MS/s and 400 Ms/s appear therefore equally suitable for sampling of BC418 detector pulses from JET NC.

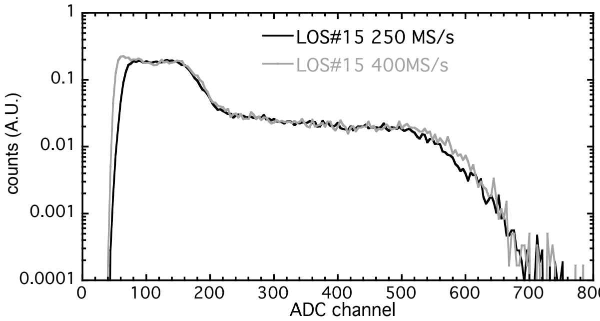


Fig. 8. Energy calibrated Na22 PHS acquired at 250 Ms/s and 400 Ms/s.

About 50 DD plasma discharges (in the range #87291 - #87595) were also acquired coupling the digitizer to a central vertical NC channel (#15); PHS data from these discharges were summed in order to have enough statistics on 14 MeV burn-up neutrons. In figure 9 the overall PHS is shown, highlighting the different regions in which contributions from DD neutrons, DT neutrons and gammas are expected.

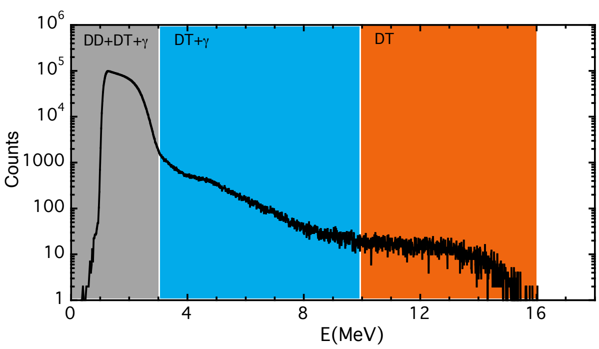


Figure 9. Energy calibrated BC418 PHS from the sum of ~50 JET discharges.

Indeed, since BC418 detectors have no neutron/gamma capabilities, the detection of 14 MeV neutrons with BC418 is obtained by setting a threshold (typically 10 MeV neutron energy) on the energy above which one can consider the counts in the PHS to be solely due to 14 MeV neutrons.

## 5. Conclusions

A new digital acquisition system for the JET neutron camera detectors devoted to the measurement of 14 MeV neutrons was designed in the frame of work-package JET4 (JET enhancements), with the objective of overcoming the limitations of the presently running analogue system (no storage of pulse data, no provision of pulse height spectra) and matching the demanding data throughput requirements of future DT campaigns.

The key design elements of the proposed system are: separate resources for processing (FPGA/PC), fast data transfer (PCIex8 bus) and data storage allocated to couples of neutron camera channels; selectable sampling rate up to 400Msps; large FPGA on-board memory; custom FPGA firmware for non-continuous acquisition of scintillator pulses.

Preliminary tests performed at JET with a portable single 2 channels acquisition board identical to that to be used for the final system indicate adequacy of ADCs input range to enable 14 MeV neutron measurements when using default HV settings of BC418 detectors and suitability of sampling rates lower than 400Ms/s in setting of energy thresholds for 14 MeV neutrons counting.

## Acknowledgments


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