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ABSTRACT

The JET neutron profile monitor provides the measurement of the neutron flux along 19 collimated lines of sight from which the neutron emissivity profile can be obtained through reconstruction based on inversion methods. The neutron detectors are liquid organic scintillators featuring n/γ pulse shape discrimination. A recent digital upgrade of the neutron profile monitor acquisition system (200 MSamples/s sampling rate per channel, 14 bit resolution) offers new real-time capabilities. An algorithm performing real-time n/γ discrimination by means of the charge comparison method is implemented in the acquisition system FPGA. The algorithm produces two distinct count rates (n and γ) that are sent to the JET real time network ready for control applications and are simultaneously stored into the JET archive together with all the samples of each pulse. The paper describes the architecture of the FPGA implementation and reports the analysis of data collected during the 2011-2012 JET campaigns. The comparison between the real-time and post-processed (off-line) neutron count rates shows an agreement within 5% for all 19 detectors. Moreover, it is shown that the maximum count rate sustainable by the acquisition system when storing raw data (~900 kHz as evaluated in laboratory tests) can be extended up to 5MHz when using the real-time implementation with no local data storage. Finally, a statistical analysis of the ratio between the line-integrated measurements from the neutron profile monitor and the neutron rate from the JET neutron monitors is presented.

1. INTRODUCTION

An FPGA (Field Programmable Gated Array)-based digital acquisition system has been recently developed for neutron and γ-ray measurements in the JET Neutron Profile Monitor (NPM) [1]. The NPM hosts 19 NE213 liquid organic scintillation detectors, one for each line of sight (LOS). The acquisition system features 19 channels at 200 MSamples/s sampling rate, 14 bit resolution and is equipped with Altera StratixII FPGAs. The FPGA manages data acquisition, raw data storage and real-time data processing which provides separated n, γ and pile-up count rates. The same data processing is also performed off-line by using a specifically developed LabVIEWTM code acting on the stored raw data [3,4]. The scintillator signals are acquired non-continuously, in discrete sets of samples (data windows); the size of the data windows varies dynamically, depending on the pulse duration and on the occurrence of other pulses during its acquisition. This Dynamic Window Data Acquisition technique (DWDA, [2]) allows to record only meaningful data and thus to increase the count rate capability of the system and to reduce the amount of stored data.

This paper provides a description of the real-time FPGA algorithm developed for count rate calculations and its tests in experimental conditions at JET.

2. FPGA ARCHITECTURE

The processing blocks of the real-time algorithm are shown in Figs. 1 and 2. They are clocked at 200MHz, while a 1 ms clock is associated with the sending of the real-time count rate data, which are delivered as UDP packets (User Datagram Protocol) by an embedded processor (Linux operating system) inside the FPGA.

The first processing block is the Pile-up Checker (Fig.1): pile-ups are defined as multiple pulses in a data window. The algorithm, in the current version, performs the n/γ separation only on single pulse data windows, and therefore in case of pile-up the only recorded datum is the number of pulses in the window (#NUM EVENTS parameter). A data window labeled as pile-up is shown in Fig.3. In this case the two pulses are separated, but often they are partially overlapped. The algorithm uses a comb-like structure: if all the comb lines encounter only one pulse the data window is declared single, otherwise it is labeled as pile-up. The comb structure is parametric: the actual values of the teeth are the best ones from the experience to minimize false negatives.

In parallel to the Pile-up Checker, the data flowing within the FPGA are sent to the Integral Calculation block (Fig.1). Such block calculates the integral of the pulse (Total INT) and two additional pulse integrals (Short INT, Long INT) the ratio of which is used as the n/γ separation parameter (charge comparison method). Short INT and Long INT are calculated starting from the sample corresponding to the maximum of the pulse and for a number of samples defined by two parameters (Short INT and Long INT) set from the external environment. Such parameters are available, for example, in the Level1 JET interface in the control room, where the responsible officer on duty can set them.

The output of this block (i.e. the integrals) is sent to the Separation Figure Calculator (Fig.1). Using the integrals a point in a "separation plane" is associated with each pulse. The point abscissa (X) is calculated from the total integral scaled by a factor called MARKER (also available in the level1 JET interface) which is used to fix the maximum value allowed before scale saturation; the ratio short/long integral, scaled by a factor (normally 4096), is used to calculate the ordinate value (Y). An example of separation plot is shown in Fig.4.

A curve composed by two straight lines is used for n/γ separation (Fig.4); the curve is defined by 5 parameters available in the level1 JET interface: Line Change (the intersection point of the two lines) and M1, Q1, M2, Q2 (angular coefficient and offset of the two lines). The MARKER, as described above, sets the full-scale range.

The last block is the Neutron/Gamma Separation Algorithm and Pile-up Calculator (Fig.2). It takes as input X and Y, #NUM EVENTS from the Pile-up Checker and the five separation curve parameters. The block checks whether the data window contains single or piled-up pulses. If a single pulse is found, it calculates the lines, identifies whether the pulse is a neutron or a γ-ray and sets to one the corresponding output bit (single, n or γ). Moreover, it increases the count of neutron, γ-ray or pile-ups, which will be sent to the real time network each millisecond. The rising edge of the FPGA millisecond clock resets all the counters and the process starts again.

3. COMPARISON BETWEEN REAL-TIME AND OFF-LINE NPM RESULTS

Data from 2011-2012 JET campaigns were analyzed. As an example, Fig.5 shows, for JET Pulse No: 83211, the total neutron count rate obtained after off-line data processing for central NPM channels #5 and #15, compared with the corresponding real-time calculation. The results are in agreement within 5%: the real-time neutron counts are slightly greater than the off-line ones due to the slightly different (optimized) setting of the separation lines used in the off-line calculation.

4. MAXIMUM SUSTAINABLE COUNT RATES

The maximum count rate sustainable by the NPM acquisition system when working in real-time is higher than when processing the data off-line (~900kHz [2,4]) due to the different amount of data transferred in the two cases: in the real-time case only the count rate data are sent through the JET network (no raw data local storage) whereas in the off-line case the data associated to each acquired pulse are first stored to the local PCs (through a National Instrument digital acquisition board) and subsequently processed.

This fact is shown in figure 6: in Pulse No: 79704 a count rate of ~100kHz for several seconds was reached in LOS #15 and this was well managed both off-line and in real-time. Later on, at t = 22s, a sudden increase of the count rate (over 2MHz) was recorded both in real-time and off-line, but the off-line recording suffered from some data loss (i.e. lower recorded maximum count rate, see Fig.6 bottom).

A laboratory test was performed to check the actual limits of the real-time processing. A pulse generator was used with a frequency modulated pulse train from 500kHz to 5MHz. The real-time data were acquired and the results are shown in Fig.7: no loss of data was observed up to 5MHz (which was the limit of the pulse generator in this modality). Note that this limit was reached using synthetic pulses and therefore all data windows have approximately the same length (about 50 samples). Acquisition of JET high-count rate discharges will enable to determine the real-time count rate limit in experimental conditions. This will be particularly useful during the foreseen JET DT campaign, in which a significant increase of the neutron emission is expected.

5. STATISTICAL ANALYSIS OF NPM AND NEUTRON MONITOR COUNT RATES

As a preliminary validation test of the NPM digital acquisition system the JET total DD neutron yield measurement (TIN/RNT time trace, provided by fission chambers) was separately compared with the sum of the off-line count rates of the NPM horizontal and vertical LOS, both expected to be roughly proportional to the neutron yield. Results of the comparison for 160 discharges between Pulse No's: 79698 and 82785 are reported in Fig.8 showing a good linearity up to $\sim 3\times10^{16}$ n/s.

The real-time KN3N measurements were compared with their off-line counterparts are shown in Fig.9. The results (74 discharges, from Pulse No's: 81271 to 81567) indicate that for neutrons the real-time counts are slightly higher than the off-line counts, while for γ-rays the opposite occurs (i.e. real-time counts slightly lower than off-line ones). This is simply due to the slightly different settings of the separation lines used, respectively, in the real-time and off-line algorithms for these discharges (as explained above in Section III), as clearly indicated by the perfect agreement of the total (neutrons + γ-rays) counts (green line).

CONCLUSIONS

The JET KN3N digital acquisition system routinely produces neutron, γ-ray and pile-up count rates for each of the 19 channels of the neutron profile monitor. These measurements are now available both as off-line and in real-time. Real-time data are accumulated every millisecond during the discharge and sent to the real-time network via an embedded processor inside the FPGA. The addition in the FPGA of an additional block for the calculation of count rates in several energy windows (for example associated with DD and DT neutrons) and the implementation of other n/γ separation methods [5] are foreseen as future upgrades.

ACKNOWLEDGMENTS

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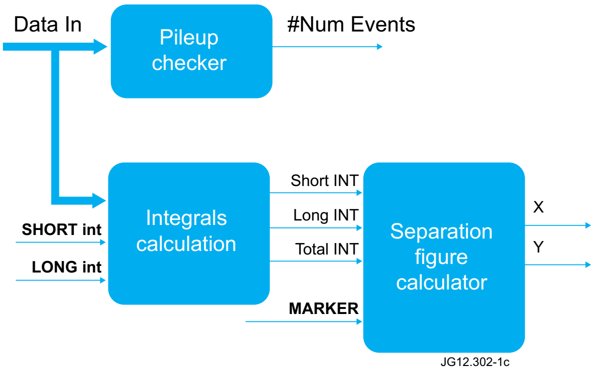

Figure 1: FPGA block diagram of the n/γ separation algorithm. The Pile-up Checker checks whether data in the current time windows are single pulses or not. The Integrals Calculation block calculates the short, long and total integrals. The Separation figure Calculator associates with each pulse a point in the "separation plane".

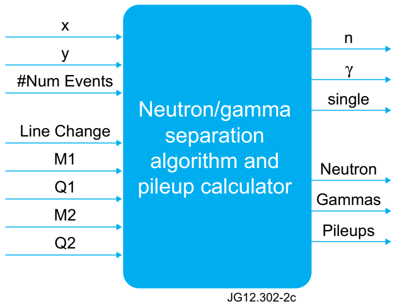

Figure 2: Neutron/gamma Separation Algorithm and Pile-Up Calculator (see description in the text).

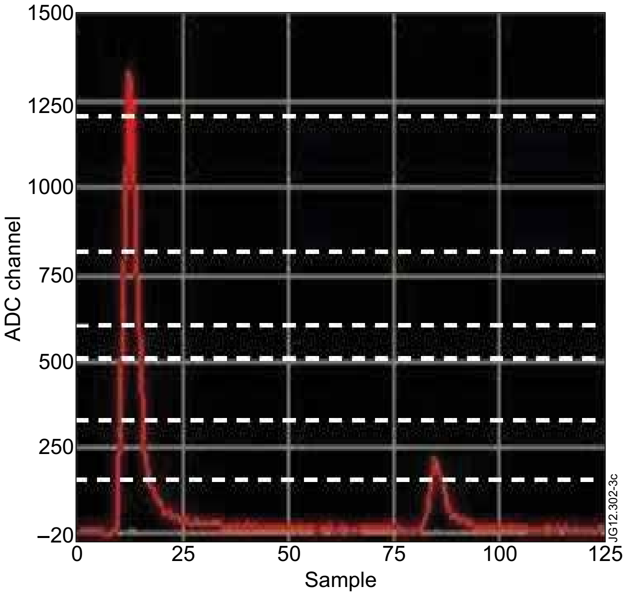

Figure 3. Pile-up data window: as the bottom line encounters two events this data window is labeled as pile-up.

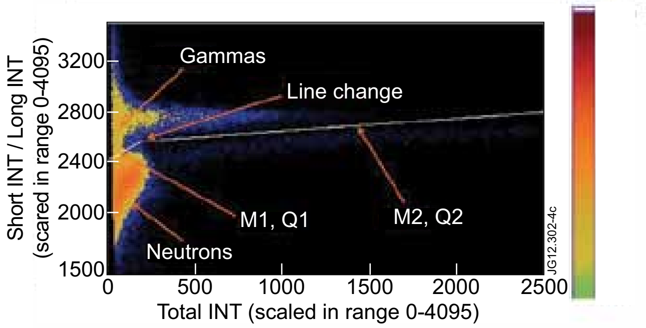

Figure 4. Typical separation figure: γ-rays and neutrons are respectively above and below the white line. The straight lines join at the Line Change point. The parameters are programmable from the JET control room.

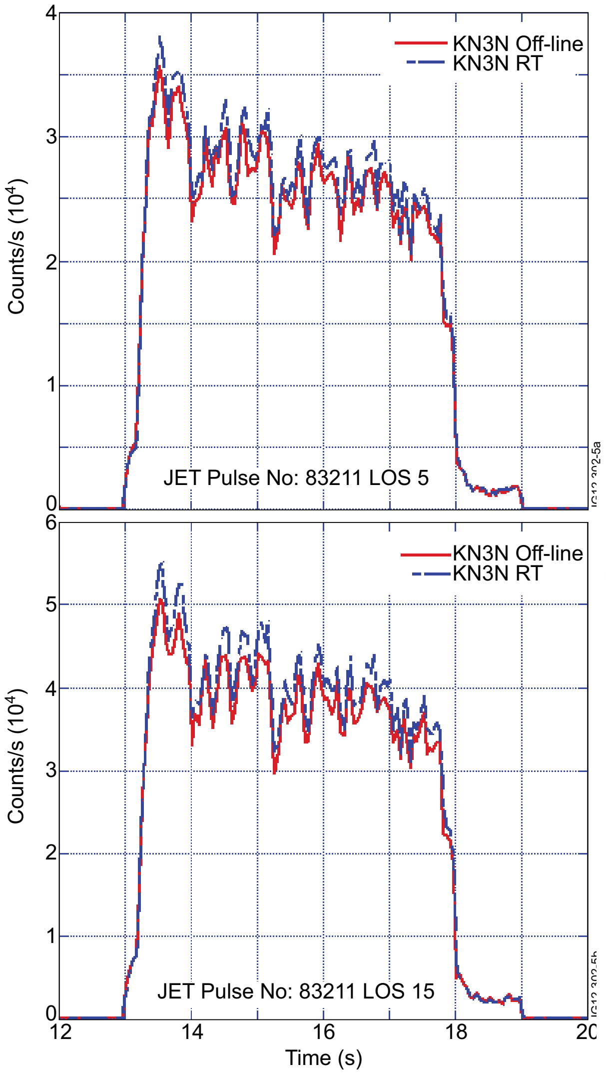

Figure 5. Comparison between real-time (RT) and off-line neutron count rates: central vertical channel #5 (top) and #15 (bottom).

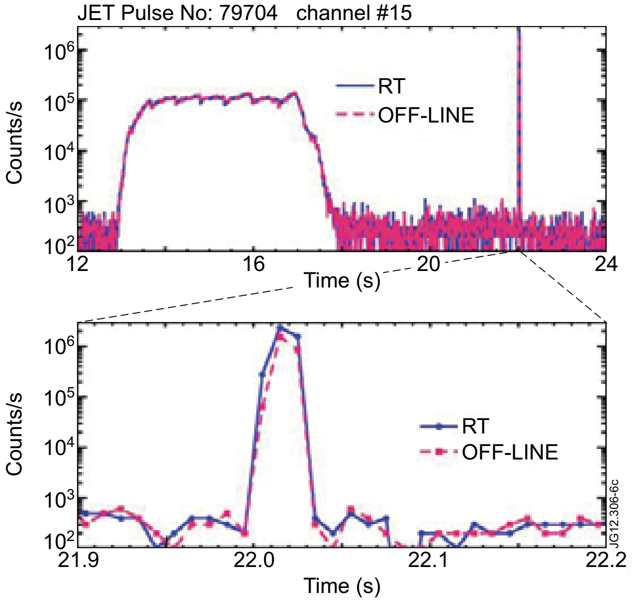

Figure 6. JET PulseNo: 79704: Both real-time and off-line acquisitions reach ~2 MHz, but some loss of data is experienced by the off-line acquisition.

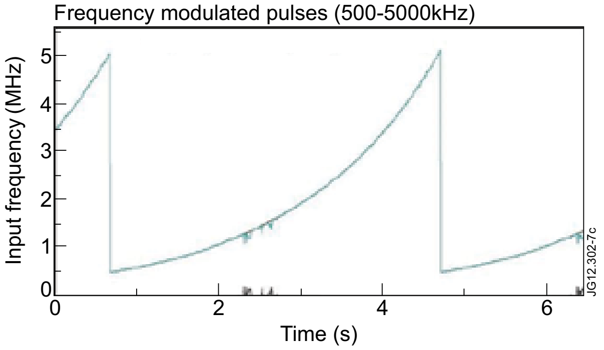

Figure 7: Laboratory test: a frequency modulated pulse sequence, from 500kHz to 5MHz, was acquired by the system without any data loss.

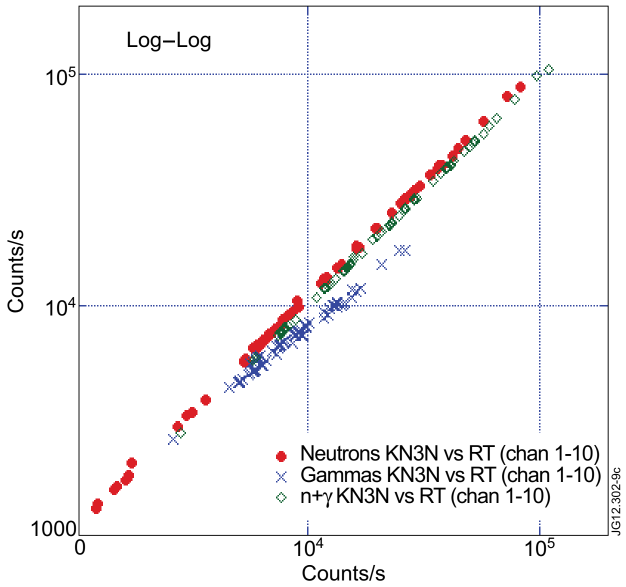

Figure 9: Comparison between real-time and off-line NPM data (horizontal LOS): neutron (red), γ-rays (blue) and neutron+γ-rays (green).

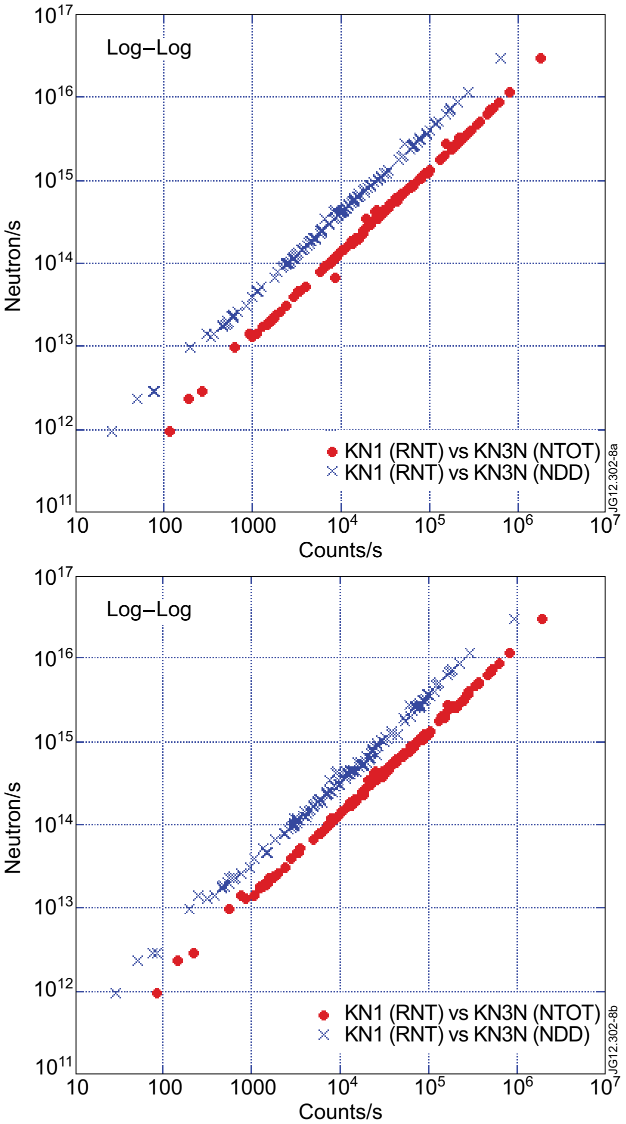

Figure 8: Comparison between the JET DD neutron yield measurements (TIN/RNT) and the sum of the count rates of the horizontal (top) and vertical (bottom) NPM LOS. Both the total NPM count rate (KN3N/NTOT, red dots) and the count rate in the energy window 1.8-3.5MeV (KN3N/NDD, blue dots) are shown. Points represent averages of 1 s around the maximum yield (rate) in the discharge. Error bars: ±5%for TIN/RNT; Poisson statistical error for the NPM.