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ABSTRACT

A Digital Pulse Shape Discrimination system (DPSD) has been used in conjunction with collimated NE213 scintillators for neutron spectroscopic measurements at high count rates (MHz range) in JET discharges (DD and DT fuelled, NBI and RF heated). The system, developed at ENEA-Frascati, is based on a commercial 200 MHz 12-bit A/D transient recorder card, which digitizes the direct output signal from the anode of a photomultiplier. Among the unique features of this novel DPSD system are the possibility of post-experiment data re-processing, high count rate operation and simultaneous neutron and gamma (γ) spectroscopy. Separation between γ and neutron (n) events is performed by means of dedicated software exploiting the charge comparison method; separate n and γ pulse height distributions and an example of neutron spectrum unfolding are shown. Implications of the DPSD in future neutron diagnostic systems on large and next step tokamaks are discussed. Subject Classification: Fusion products, neutrons.

1. INTRODUCTION

Neutrons and γ-rays interacting with NE213 scintillators produce slightly different light pulses: this property is used to discriminate between neutron and γ-ray events by means of the pulse shape discrimination (PSD) technique. The light pulses in the scintillator are the combination of a fast scintillation component (τ_F ~ 3-4 ns) and several slow components (τ_S up to 270 ns). A typical n/γ discrimination method is based on the charge comparison method: each pulse is integrated for two different time intervals ($\Delta\tau_F$ and $\Delta\tau_S$) corresponding to the fast and slow scintillation components; the value of the ratio Q_S/Q_F, where Q_S and Q_F are the charges integrated during $\Delta\tau_S$ and $\Delta\tau_F$, provides, independently on the amplitude of the pulse, the indication whether a neutron or a γ-ray event has taken place.

NE213 detectors are routinely used for neutron measurements in the mixed neutron and γ-ray fields of nuclear fusion experiments. At JET (Joint European Torus), the world largest experimental fusion device, NE213 scintillators coupled to analog PSD modules are in operation in the 19 collimated channels of the radial and vertical neutron cameras and in a neutron spectrometer system (detector B described in Section II). These PSD modules are based on the charge comparison method and normally operate up to ~200 kHz output count rate1; moreover, analog PSD modules do not allow any reprocessing of the signal data after the experiment has taken place and therefore a constant and careful check of all module settings is necessary in order to ensure full reliability of the results.

In this paper (Section II) it will be shown how an analog n/γ PSD module can be effectively replaced by a digital pulse shape discrimination system (DPSD), which is simply a computer code performing the analysis of scintillator pulses acquired by an ultrafast A/D (analog-to-digital) transient recorder. The successful application of this system to high resolution and high count rate neutron spectroscopy measurements with NE213 in JET will be given in Section III. The advantages of DPSD compared to analog PSD will be discussed in Section IV.

2. DPSD SYSTEM DESCRIPTION

The DPSD system for organic scintillators recently developed at ENEA-Frascati[2] is based on a commercial 200 MHz 12-bit A/D transient recorder PCI card (Strategic Test model UF.30253[3]), which allows digitization of scintillation pulses, and a dedicated LabVIEW™ software which provides data visualization, separation of n and γ events based on the charge comparison method and generation of pulse height distributions (both for neutrons and γ-rays).

The direct output signal from the photomultiplier anode is DC coupled to the fast transient recorder and digitized. Two input channels can be sampled simultaneously at 100 MHz or one channel at 200 MHz. Various data recording modes have been tested: (1) Sampling only those pulses which are above a preset threshold value (the duration of the sampling for each pulse can also be preset, for example 32 or 96 samples) by using the internal trigger mode enabled by the signal connected to the input channel. The inputs are sampled continuously and, after trigger recognition, a post-trigger counter is started; when this counter reaches its programmed value recording is stopped, and the post trigger data plus a preset number of pretrigger data are read and stored on a PC: during data transfer data acquisition is inhibited. The time history of all events can be reconstructed enabling a specific card option (time stamp), which allows the recording of the time of occurrence of each trigger event. This mode is suitable for laboratory measurements where the frequency of pulses is constant and not very high (e.g.: 1 kHz) and acquisitions for long time intervals can be performed. (2) Sampling the input signal continuously after a start trigger until the on-board memory is full (or a stop trigger is given). In this case the data are first stored on the on-board memory of the card (256 MSamples) and transferred to a PC only after the acquisition is completed: this mode is suitable for acquisition of pulses at high frequency (even several MHz) with no loss of data, the only drawback being the limited acquisition duration (~1.3 s corresponding to 200 Msamples/s with 12-bit samples). (3) Multiple recording. In this mode an external trigger signal is used and several triggered pulses (all with the same preset number of samples) can be recorded without restarting the hardware. Data reading and storage to PC is performed after the on-board card memory, or a preset fraction of it, is full: this mode can be used to acquire high frequency pulses for long time intervals; no loss of events occurs within the duration of each buffer, but events are lost during the buffer readout. Also in this case the time structure of the registered events can be reconstructed using the time stamp option.

In the experiments at JET, acquisition mode (2) has been employed at the maximum sampling frequency (200 MSamples/s with 12-bit samples). Moreover, in order to simplify the transportation and the set-up of the system in the JET environment, the fast transient recorder card has been installed on a 2 slot CardBus PCI Expansion System (Magma model CB24) which consists of a CardBus card, a shielded and high-speed expansion bus cable, an expansion motherboard and a chassis with a power supply; the CardBus card was connected to a Toshiba Satellite Pro laptop (1.7 GHz Pentium IV with 512 MB RAM and WINDOWS XP).

The software developed for the analysis of the continuous stream of acquired data consists of several distinct stages: (a) filtering for removal of low frequency noise; (b) pulse peak identification (above a preset threshold); (c) pulse re-organization in windows of fixed length (typically 96 samples with 20 samples pre-peak); (d) pile-up identification: windows containing one event are stored as 'single pulses', while windows containing more than 1 event are labeled as pile-up and stored in a separate file; 'total' and 'single pulse' count rates are available at this stage; (e) pulse integration: each pulse is integrated in two time windows starting from the peak of the pulse (25 ns and 120 ns) for n/γ discrimination and in another time window, lasting 150 ns ÷ 325 ns from the beginning of the pulse, for pulse height analysis (PHA); (f) 3D plot in Q_F-Q_S space for graphical n/γ separation and subsequent determination of neutron and γ-ray pulse height distributions.

3. JET MEASUREMENTS: EXPERIMENTAL SET-UP AND RESULTS

Two NE213 detectors were installed along the same line of sight, intercepting the major radius R=2.93 m, through a collimating structure in the JET roof-lab; detector A was facing the plasma, while detector B was positioned on the back of detector A. Detector A had been fully characterized at PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany) in terms of response function and it is therefore optimized for high energy resolution neutron spectrometry: it is a 50.8 mm x 50.8 mm NE213 coupled to a 12-dynode XP 2020 PMT; an LED is mounted on this detector and its pulses (at a frequency ~1 kHz) are used for monitoring PMT gain variations. Detector B is routinely used at JET for neutron spectrometry; it is a NE213 bubble-free BA-1 cell (dimensions: 50 mm diameter by 20 mm thick) coupled to a Thorn EMI 9815B 52 mm diameter fast linear focussed 10-dynode photomultiplier (PMT). In both detectors ^{22}Na γ-ray sources were installed for in situ calibration purposes. Detector A was directly connected to the DPSD system, while Detector B signals were split and fed into two 300 MHz amplifiers[5] for simultaneous acquisition with the standard JET analog PSD and with the DPSD.

Neutron measurements were carried out during the Trace Tritium Experiment in September 2003: data were collected with detector A in 15 discharges and with detector B in 7 discharges. Various plasma conditions (neutral beam injection (NBI) and radio frequency (RF) heated discharges) and different fuel compositions (deuterium (DD) and deuterium-tritium (DT)) have been studied. Total count rates up to 2 MHz were measured by detector B and up to 0.6 MHz by detector A. The time traces are in agreement with those produced by the fission chamber neutron rate monitors (Fig.1 referring to a DT discharge with 90 ms tritium blip and 15 MW NBI). Pulse height distributions obtained simultaneously for neutrons and γ-rays in a DT discharge and for neutrons only in various plasma scenarios are shown respectively in Fig.2 and Fig.3. The n/γ separation obtained for a DT discharge is shown in Fig.4 as 3D plot in Q_F-Q_S space: a color scale is used to indicate the number of events corresponding to a given Q_F,Q_S set.

The 12-bit resolution of the transient recorder card allows to cover a large neutron energy range, including at the same time the 2.5 MeV and 14 MeV neutrons, respectively from DD and DT reactions, as shown by the neutron spectra (Fig.5) obtained for a DT plasma by means of unfolding analysis[6] from the neutron pulse height distribution. The peak produced by the LED (which is used for energy calibration) is also shown in the insert: in this case, due to the different time duration of the LED pulses compared to the radiation pulses, the third time integral (as described in Section II) has been carried out over 325 ns.

4. DISCUSSION

The n/γ DPSD system for NE213 scintillators developed at ENEA-Frascati was employed for the first time in a DT fusion experiment at JET and its high performance has been demonstrated: n/γ separation and neutron and γ pulse height spectra have been obtained in several plasma discharges up to 2 MHz total count rate. Separation between neutron and γ events is made through dedicated software which applies the charge comparison method to the digitized signals.

Compared to analog PSD, the new technique offers several advantages including simultaneous n and γ PHA at high count rates, data reprocessing and pile-up correction possibilities (the analysis and recognition of pile-up events, based on neutral network analysis, is presently under development in a collaboration with Politecnico di Bari, Italy)[7] and dynamic range adequate to cover both DD and DT neutron applications.

Further development of the DPSD technique will permit its application as a standard tool for neutron spectroscopy detection systems of future fusion devices (e.g. ITER) where reliable operation of several neutron detectors is required: NE213 and DPSD represent a cheap, compact and flexible option.

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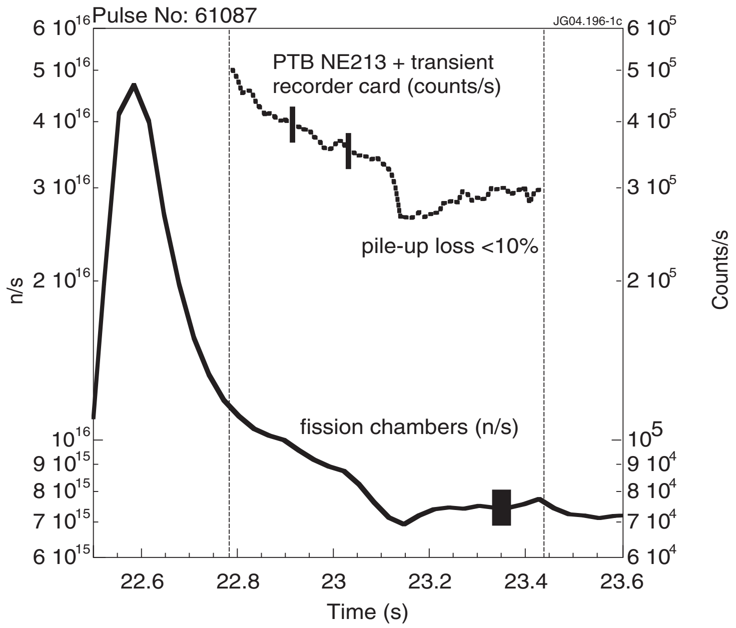

FIG.1: Comparison between neutron rate from calibrated fission chambers and total count rate from PTB NE213 coupled to DPSD system (96 samples pulse window) in JET DT discharge #61087.

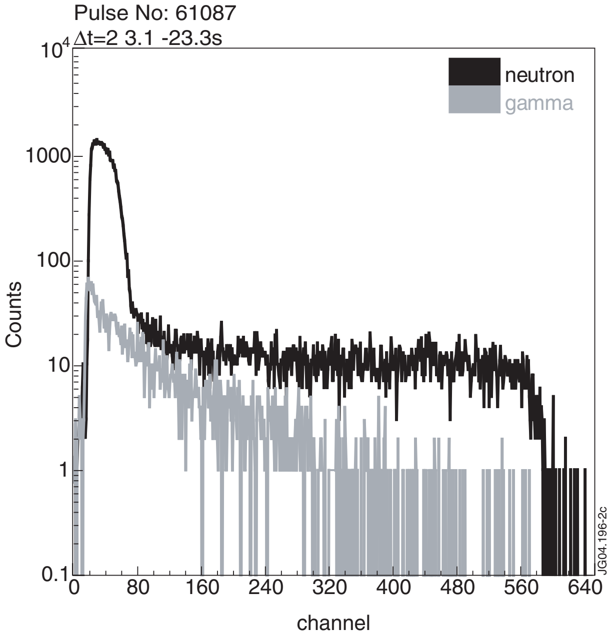

FIG.2: Neutron and γ-ray pulse height spectra for DT discharge #61087.

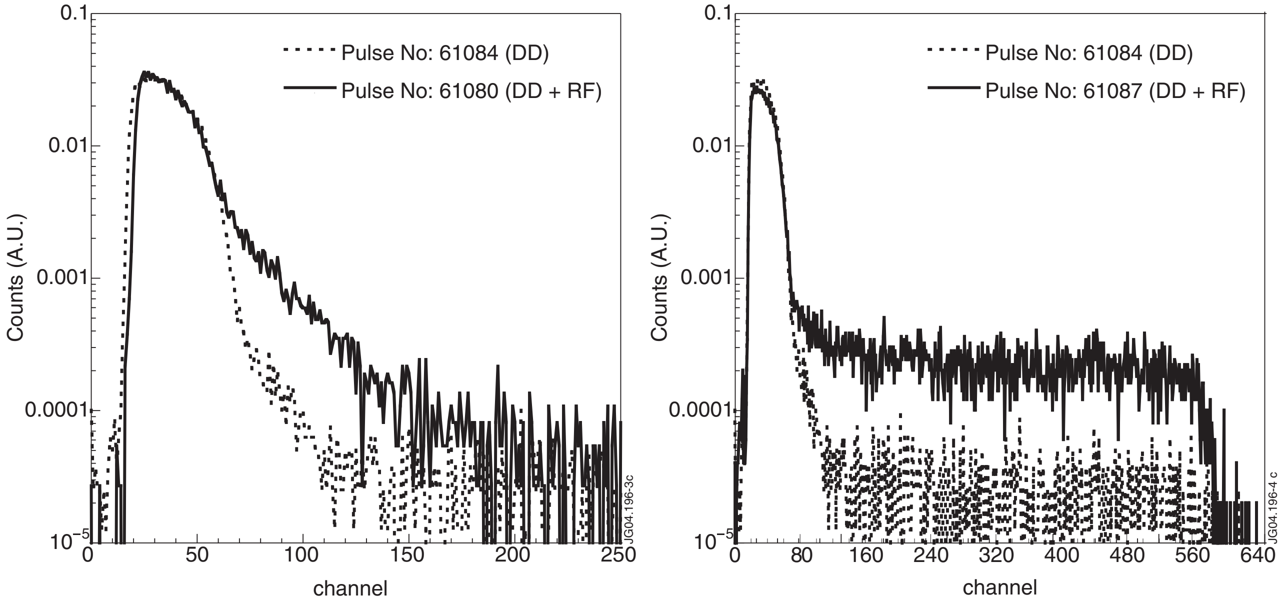

FIG.3: Neutron pulse height spectrum with PTB NE213 and DPSD: (a) DD and DD + RF (4.5 MW ICRH); (b) DD and DT discharges.

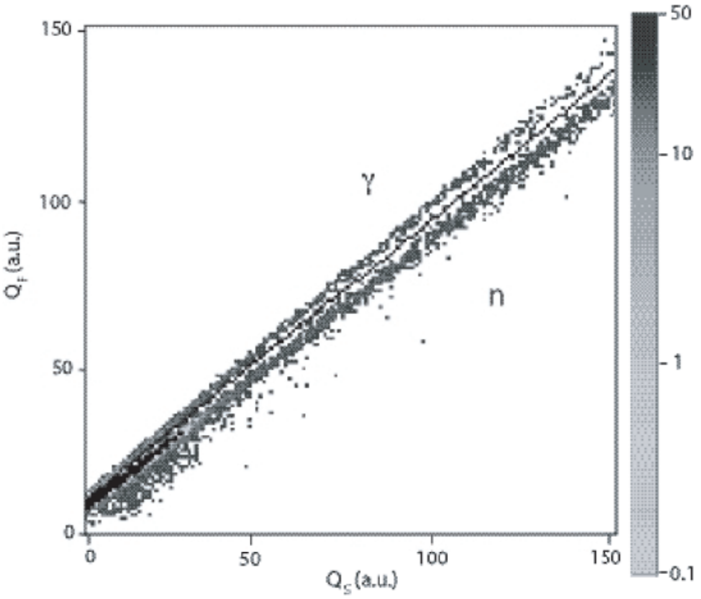

Fig.4, B. Esposito et al., Rev. Sci. Instrum.

FIG.4: Discharge #61087: n/γ separation with PTB NE213 and DPSD system (Δt=23.1 -23.3s).

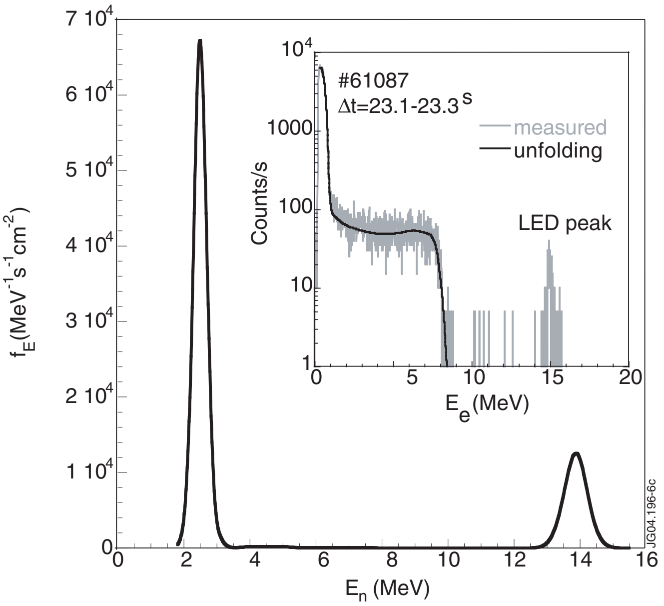

FIG.5: Neutron spectrum obtained by unfolding the neutron pulse height distribution (shown in the insert) of DT discharge #61087.