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INTRODUCTION

Neutron emission spectrometry is a versatile tool for diagnosing the fuel ions of fusion plasmas. Information on parameters such as ion temperature, plasma rotation, n_T/n_D ratio [1] as well as the properties of high-energy ions [2] (originating from external or internal heating) can be provided. Neutron spectrometry can be performed with several techniques, each offering different capabilities, advantages and disadvantages. Broadly speaking, there are two types of instruments; compact spectrometers [3,4] and designed spectrometric systems. The detectors in the former category can be used as stand-alone spectrometers, but in fusion have their most important application in neutron cameras. Here we report on developments of two techniques belonging to the latter category, namely, the Time-of-Flight (TOF) and the Thin-foil Proton Recoil (TPR) techniques, and their performance in a Deuterium-Tritium (DT) campaign.

1. THE TIME-OF-FLIGHT TECHNIQUE

Time-of-flight neutron spectrometers have been used at JET since 1986. The time-of-flight spectrometer TOFOR [5], installed in 2005, delivers data at high rates (maximum of 400kHz) of high quality in signal-to-background (S/B) and energy resolution (FWHM/E ≈ 8.3%). The response function of TOFOR is Gaussian-like but influenced by multiple scattering events on the low energy side (high time-of-flight, see Fig. 1a). To ensure high count rate capability, the original TOFOR was equipped with fast time digitizers, which, however, lack the possibility to provide simultaneous pulse-height information. Figure 1a shows simulated time-of-flight spectra of TOFOR for mono-energetic 14MeV (blue) and 2.5MeV (red) neutrons. The flat part of each spectrum on the high time-of-flight side is due to multiple scattering. Note that the multi-scatter tail of the 14MeV response (peak at 27ns) limits the ability to resolve the 2.5MeV emission (peak at 65ns) in cases with a substantial fraction of T fuel. A further complication for the TOF technique is that the S/B decreases linearly with count rate due to a disturbing presence of random coincident events [6]. This will particularly influence the performance in high-rate operations, such as in DT. The problem is illustrated in Figure 1b, where two TOFOR time-of-flight spectra are shown. The spectra were collected with different TOFOR settings; one which accepts almost all signals for acquisition (red) and one which discriminates against low pulse-height events (black), basically excluding all 2.5MeV DD events. Note that when the 2.5MeV events (and their associated random coincidences) are rejected the low-intensity 14MeV DT peak clearly emerges from the background, due to a considerable improvement in S/B. Clearly, the multiple scattered and random events limit the ability of the original TOFOR to resolve weak signatures in the neutron spectrum.

Developments in electronic Data AcQuisition (DAQ) hardware now allow for acquisition of correlated time-of-flight and pulse-height information on an event-by-event basis. In close collaboration with the manufacturer, we have developed a waveform digitizing DAQ card for fusion time-of-flight applications [7] and tested it in the lab. The configuration is a four-channel card, with 12 bit ADC resolution, 1GHz sampling rate and with flexible inter- and intra-card

time synchronization capabilities. Three cards have been purchased and tested with pulses from generators, LEDs and scintillators exposed to radioactive sources and cosmic rays. Time synchronization performance was verified with a relative time spread between cards of <5ps over several s of operations. Different options for common start of the cards were explored. All results indicate the cards meet the demands of the intended time-of-flight application. For example, in a scintillator coincidence measurement using cosmic muons, the electronic contribution to the time resolution was estimated to less than 0.7 ns, a factor 3 improvement compared to the original TOFOR. As shown in Fig. 1b, combined time and pulse-height information can be used to significantly reduce the intensity of the random coincident events in the time-of-flight spectrum as well as reducing the influence of multiple scattering events [6]. A small improvement in energy resolution can also be expected, from 8.3% to 6.7%, due to a more exact event time determination using digital constant fraction techniques.

2. THE THIN-FOIL TECHNIQUE

In the thin-foil technique, a collimated neutron beam strikes a thin hydrogen-rich foil. A fraction of the neutrons scatter elastically on the hydrogen of the foil resulting in recoil protons. The proton energies are then determined in (conceptually) two ways; by momentum separation in a magnetic field [8] or through energy deposition in a detector [9,10]. The magnetic proton recoil spectrometer (MPRu) at JET is of the magnetic type and offers a flexible system in terms of efficiency and resolution. It utilizes modern digital sampling electronics and has efficient background suppression: a $S/B = 10^4$ is estimated in DT operations. The MPRu has recently been enhanced. First, a thin layer of Gadolinium (paint) has been applied to areas close to the detector to reduce gamma background from thermal neutron capture. Second, a neutron flux monitor has been installed in the MPRu Line Of Sight (LOS) behind the spectrometer in order to enhance its capability to determine the neutron yield in D operations. Compared to the magnetic technique, the non-magnetic TPR technique has some attractive properties such as higher efficiency and simplified interfacing, as shown in our previous simulation studies [10]. We have now set up a more detailed TPR simulation model, to guide in the design of a proof-of-principle system. The TPR performance was evaluated in terms of resolution and efficiency as a function of the instrument geometry (foil-to-detector distance and foil thickness) using a silicon detector for the proton energy determination. The modelling results have been used to define three 14MeV working points, ranging in efficiency from $\varepsilon = 5 \cdot 10^{-4}$ cm^2 to $\varepsilon = 5 \cdot 10^{-5}$ cm^2, with a reciprocal dependence in resolution between FWHM/E = 10% and FWHM/E = 2.5%. A TPR system can be designed to change the working point in between discharges, which allows for the same flexibility as the MPRu. Furthermore, a detailed MCNPX and FISPACT model has been developed to evaluate the expected background seen by the silicon detector using different local vacuum vessel materials. The model indicates a best S/B = 200 when an Aluminium vacuum vessel is used.

3. NEUTRON SPECTROMETRY IN A DEUTERIUM-TRITIUM CAMPAIGN AT JET

In a future DT campaign at JET [11], several neutron spectrometry hardware upgrades and method developments could be evaluated. First, a TPR system should be tested, comparing its performance with simulations and other diagnostics, such as the MPRu and TOFOR. This comparison would help in the design of a high resolution neutron spectrometer system for ITER. Second, a TOFOR system equipped with the new acquisition cards should be tested in terms of its broad band spectrometry capability, S/B and improved count rate capability. In addition, several analysis methods should be tested and further developed. For example, the determination of the fuel ion ratio n_T/n_D is of great interest to ITER and the JET system of neutron spectrometers can be used to develop the method of determining n_T/n_D from neutron spectral information [1]. Furthermore, the availability of several spectrometers capable of measuring the DT neutron flux along different LOS (MPRu, TOFOR and others) allows for improved measurements of the fuel ion distribution function, which provides important input to plasma modelling and can give improved estimates of e.g. the thermal T_i, plasma rotation and $Q_{thermal}$. Finally, the higher efficiency of a TPR system could contribute to improve the alpha knock-on measurements previously performed with the single MPR instrument [12].

CONCLUSIONS

We have tested specifically developed, state-of-the-art waveform digitizers with time stamping capabilities for fusion neutron time-of-flight instrumentation and found their performance in terms of pulse-height resolution and timing properties to be suitable for the intended application. Results from simulation studies and laboratory tests with a variety of input signals have shown that the digitizers can significantly reduce the disturbing influence of random coincidences and multiple scattered events in the time-of-flight spectra, as well as improve the time (energy) resolution. We estimate that installation of the new digitizers with a fusion neutron time-of-flight spectrometer, such as TOFOR at JET, should make it possible to expand the operational range of such an instrument into D(T) and possibly DT scenarios.

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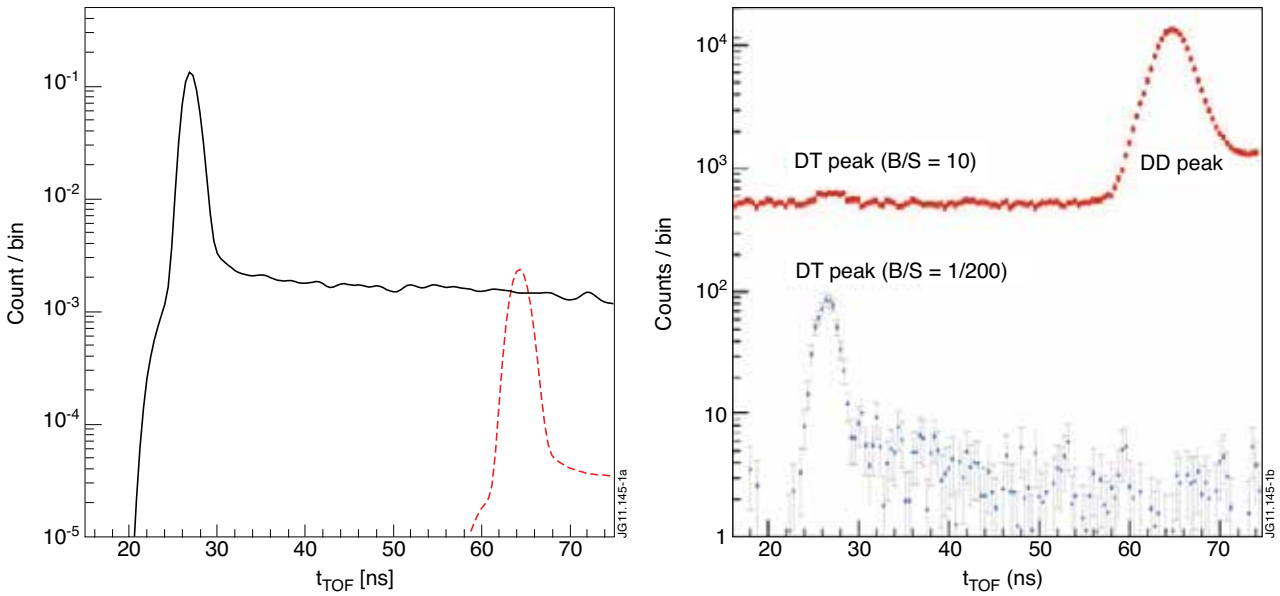

Figure 1: (a) Simulated time-of-flight spectra of TOFOR for 14MeV (blue) and 2.5MeV (red) neutrons. The intensities correspond to a fuel mix with a considerable fraction of T. (b) TOFOR experimental spectra of JET Pulse No's: 76193-210 with (blue) and without (red) discrimination of low (here, 2.5MeV) pulse-height events.