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# Measurements of DD and DT Fusion Neutrons Using a Single-Crystal Diamond Detector at JET

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## ABSTRACT

A new prototype of a single-crystal diamond detector has been tested at JET for measurements of DD and DT neutrons. The detector was installed in the JET torus hall on a collimated line of sight, which is shared with other neutron diagnostics, the MPRu neutron spectrometer and the NE213 scintillator. The results of the first measurements in the JET campaign C31 are presented in this paper. The measurements exploited for the first time the possibility of performing good resolution spectroscopy measurements of 2.5 and 14MeV neutrons using fast charge preamplifier combined to a digital acquisition system. The prototype detector has been developed for operation at very high cont rate applications, such as the one expected from high power DT plasmas. A distinction should be made in the neutron detection between neutrons of energy below and above 6MeV. The 2.5MeV neutrons from DD reactions, which are measured using elastic scattering on carbon nuclei, provide small amplitude signals and require a dedicated preamplification stage. This is the main component of the neutron energy spectrum in JET deuterium plasmas. Neutron spectrometry of 14MeV DT neutrons is possible via the $^{12}C(n,\alpha)^{9}Be$. Preliminary measurements of the 2.5MeV neutron emission and of the 14MeV triton burn-up neutrons, which represents about 1/100 of the neutrons in JET deuterium plasmas, are presented.

## 1. INTRODUCTION

The applications of Single-crystal Diamond Detectors (SDDs) are rapidly growing: they range from UV detection for astrophysics and plasma physics, to minimum ionizing particle detection in particle physics experiments, X- and γ-ray detection for radiology and radiotherapy, and proton beam sensors. SDD applications for fast neutron measurements include neutron emission monitors and neutron spectrometers [1-4].

Neutron detection is based on the collection of the electrons/holes pairs produced by charged particles generated by neutron reactions with carbon. The most important reactions producing charge particles are the elastic channel, the $^{12}C(n,\alpha)^{9}Be$ reaction (the Q-value is -5.7MeV) and the $^{12}C(n,n')3\alpha$ reaction (the Q-value is -7.3MeV). Measurements at accelerator facilities of the fast neutron response are reported in literature [5-7]. A distinction should be made between Deuterium-Deuterium (DD) and Deuterium-Tritium (DT) neutrons. High resolution neutron spectrometry of 14MeV neutrons is possible via the $(n,\alpha)$ reaction of neutrons on carbon nuclei, which is enabled for neutron energies above 6.17MeV. Spectroscopic measurements for 2.5MeV neutrons are possible only using the recoil carbon nuclei spectrum.

Diamond detectors were tested in the past on tokamak devices with experiments aimed to DT neutron measurements, using the $^{12}C(n,\alpha)^{9}Be$ reaction, or to DD neutron measurements using lithium coated diamond, which are based on the capture reaction on lithium [8-11]. In the present work the main novelties are (1) the first simultaneous DD and DT neutron measurements, based on elastic scattering on carbon and on the $^{12}C(n,\alpha)^{9}Be$ reaction respectively, and (2) the use of a fast electronic chain to investigate the possibility of performing high rate measurements with good energy resolution.

SDDs have properties such as compact dimensions, radiation hardness, insensitivities to magnetic fields, that make them interesting candidates for neutron measurements on next generation tokamaks. In particular, in a fusion plasma experiment, the fusion power can be determined from collimated neutron measurements with a high-resolution and a well-characterized neutron spectrometer, combined with plasma profile information provided by a neutron camera system [12]. Moreover, high resolution neutron spectroscopy provide diagnostic information on the reactants energy distribution, and can be used for fast ion studies, as demonstrated with measurements in present day tokamaks [13-17].

## 2. EXPERIMENTAL

The prototype diamond detector installed at JET features a nominal active volume of 4.7x4.7mm$^2$ area times 0.5mm thickness. The electrical aluminum contacts have 4.5mm diameter. The collimated Line of Sight (LoS) is shared with the MPRu spectrometer, double crossing the plasma core tangentially [18-21].

A high voltage bias of +400V is applied on the diamond contacts. A fast charge preamplifier is the first element of the read-out electronics, sitting 20cm away from the detector, just clear from the neutron beam. Figure 1 shows a picture of the detector, mounted on a mechanical support, and the amplifier. After the first amplification stage, the signal is split in two lines by a Fan In Fan Out. One of the two output signals is fed directly to a digitizer, with 1 Gsample/sec sampling frequency and 10 bits resolution [22]. The other line goes through a second amplification stage, a current amplifier in this case, before being fed in a second channel of the same digitizer. The reason for having two electronic chains is that signals form DT and DD are different in amplitude by a factor of 20, due to the different nature of the neutron interaction with carbon nuclei.

Figure 2 shows an example of a signal acquired during the calibration with the final setup at JET. The signal is about 20nsec wide at half maximum, which is fast enough for future applications at MHz count rates, such as the next DT campaign at JET in this position. Pulse height analysis is done off-line using a trapezoidal filter algorithm.

The calibration at JET was performed with a triple-alpha source ($^{241}$Am, $^{239}$Pu and $^{244}$Cm) placed in front of the detector. The measured spectrum is shown in figure 3. An energy resolution (FWHM/E) of 2.2% is measured at 5.2MeV. This value is a good result for spectroscopy on fusion plasma, since it is considerably smaller then the broadening due to the ions kinematics (about 5% on DT thermal plasmas). Moreover, it must be stressed the fact that this results was obtained with a fast acquisition chain, which is capable to handle count rates up to few MHz [7].

## 3. NEUTRON MEASUREMENTS AT JET

The detector began to measure in July 2013 during the JET campaign C31. Figure 4 shows the neutron emission time traces measured with the SDD for three different JET discharges with NBI power of 11MW, 17MW and 20MW. It is possible to notice the different intensities of the neutron emission and the different shape of the time traces due to NBI modulation of different plasma scenarios. The time resolution was set to 0.5sec. A better time resolution would be possible with an increased neutron flux, which would result in improved statistics.

Figure 5 shows the measured Pulse Height Spectrum (PHS) due to DD neutrons. In order to improve the statistics, 45 discharges have been summed. The discharges feature an average NBI power ranging from 12MW to 20MW. The PHS has the characteristic box shape for the recoil ions energy distribution. The shoulder is at 0.69MeV, as expected from the maximum energy deposited by back-scattering of 2.5MeV neutrons on Carbon [23]. The broadening of the edge is due to both the detector resolution and plasma kinematics.

The deposited energy spectrum for DD neutrons, due to recoil carbon nuclei, was simulated using MCNP [24] Monte Carlo simulations, considering the contribution of direct neutrons from the plasma as well as neutrons scattered in the line of sight and gamma rays. The model geometry consist on the bare diamond volume and aluminium contacts. Concerning the direct neutrons from the plasma, a reference neutron spectrum for the NBI has been used, about 400 keV wide at half maximum. A convolution with a 5% (FWHM) wide Gaussian takes into account the resolution of the detector itself.

An existing MCNP model of the MPRu line of sight has been used to simulate the energy distribution of the scattered neutrons and of the $\gamma$-rays emitted in the LoS. Both scattered neutrons and $\gamma$-rays come mostly from the polyethylene beam-dump, which is right behind the diamond detector.

PHS was measured for the 14MeV DT triton burnup neutrons, as it is shown in figure 6. In a deuterium JET plasma about 1% of the neutrons comes from DT reactions [25-27]. Considering the very low 14MeV neutron fluxes, PHS have been summed during one month of JET operation. In this case the (n,$\alpha$) peak is present, since neutron energy is above the threshold $E_{th}$ = 6.17MeV. The peak is very wide (about 2MeV FWHM) due to the kinematics of triton slowing down in the plasma, in good agreement to what was expected from [26]. For the same reason, the (n,3$\alpha$) continuum edge is broadened.

Neutron measurements will continue in the next JET campaigns with deuterium and DT plasmas. In particular, the possibility to perform plasma diagnostics using high resolution neutron spectroscopy will be investigated, with particular attention to fast ions measurements.

## OUTLOOK AND CONCLUSIONS

In this paper the first simultaneous measurements of DD and DT neutrons are presented. The measurements exploited the possibility of performing good resolution spectroscopy of 2.5 and 14MeV neutrons with fast electronics that allows for high count rates and features at the same time good energy resolution. The deposited energy spectrum for DD neutrons, due to recoil carbon nuclei, was calculated using Monte Carlo simulations, considering the contribution of direct neutrons from the plasma as well as neutrons scattered in the line of sight and gamma rays. Comparison of the calculated spectrum with the measured one shows a good agreement.

The results presented here will be the basis for further development of diamond detectors for neutron diagnostics for JET and for the next generation burning plasma experiments. A new compact neutron spectrometer based on diamond detectors is being developed at the Milan CNR research centre for installation at JET. The project will develop a matrix of Single-crystal Diamond Detectors which will be installed in the Roof Laboratory, aiming in particular at 14MeV neutron measurements during the next DT JET campaign.

## ACKNOWLEDGEMENTS

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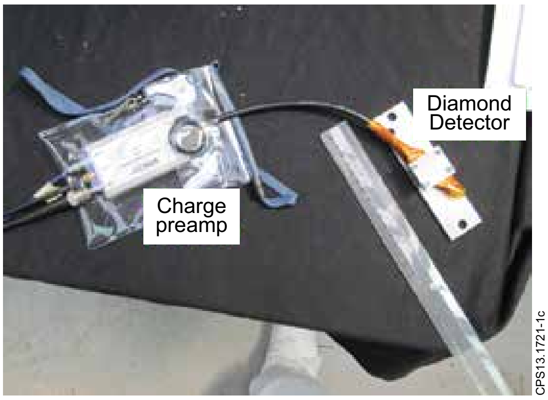

*Figure 1: Picture of diamond detector and preamplifier readied to be installed at JET.*

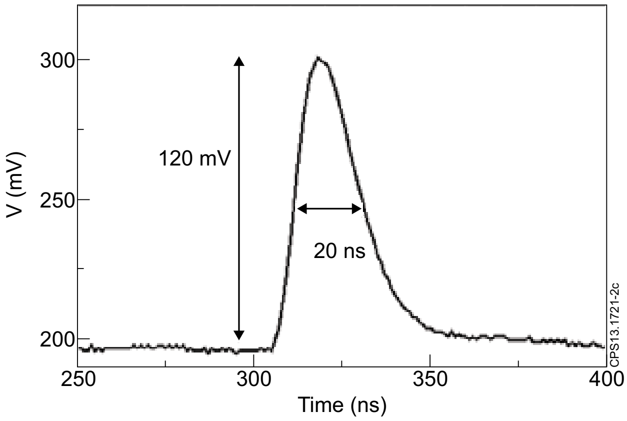

*Figure 2: Example of a signal acquired during the calibration with the final setup.*

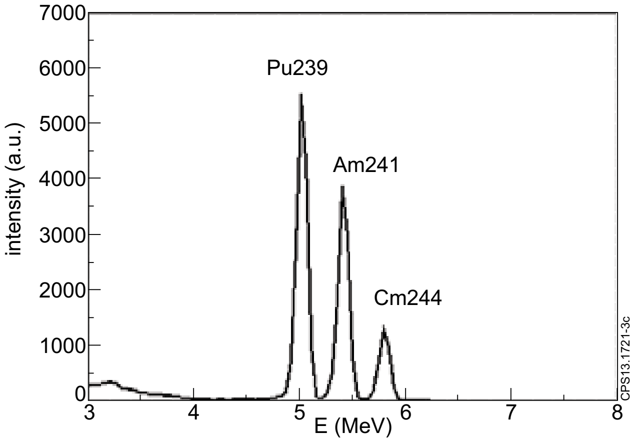

*Figure 3: Triple-alpha calibration spectrum measured with the SDD.*

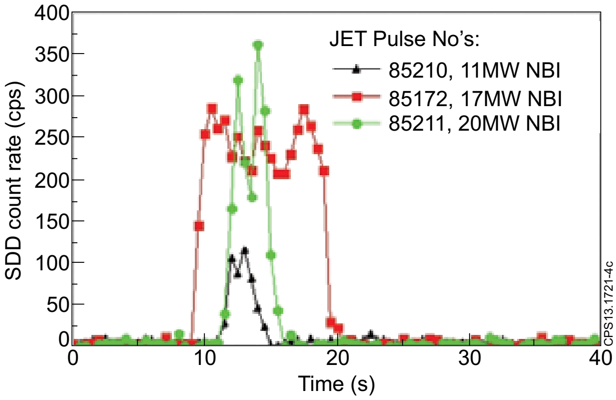

*Figure 4: Neutron emission time traces measured with the SDD for JET Pulse No's: 85210, 85211 and 85172.*

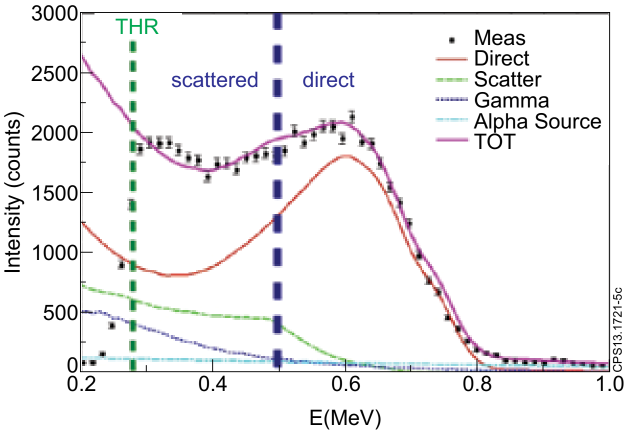

*Figure 5: Pulse height spectrum measured with the SDD for DD neutrons, compared to MCNP simulations. Dashed lines identify a deposited energy region where direct neutron contribution is dominant.*

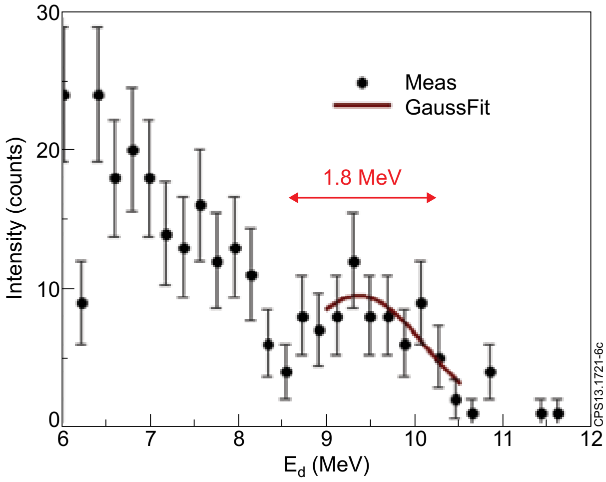

*Figure 6: Pulse height spectrum measured with the SDD for DT neutrons and Gaussian fit of the (n,α) peak.*