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Neutron emission spectroscopy measurements with a single crystal diamond detector at JET

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Single crystal diamond detectors are under consideration for neutron measurements in the neutron camera of high performance fusion devices, such as ITER. Being compact, insensitive to magnetic fields and gamma-ray background, they offer advantages with respect to the more conventionally used liquid scintillators, also in terms of their better resilience to neutron damage. An additional feature is offered by their intrinsic high energy resolution (at the level of a few %), which may enable spectroscopy measurements along multiple line of sights, complementing the information attainable by a non compact, dedicated neutron spectrometer on a single line of sight.
In this work we present a selection of neutron spectroscopy measurements with a single crystal diamond detector performed at JET in the recent experimental campaigns (2013-2014). After a brief introduction on the instrumentation, examples of neutron spectra measured in plasmas heated with neutral beam injection and radio-frequency waves are presented and their shapes interpreted in terms of the energy distribution of fast deuterons accelerated by the auxiliary heating. Prospects for future neutron measurements in JET deuterium-tritium plasmas using diamond detectors are finally addressed.

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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, 2, 3, 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 are neutron elastic scattering on ^{12}C, the ^{12}C(n,α)^{9}Be reaction (Q-value of -5.7 MeV) and the ^{12}C(n,n')3α reaction (Q-value of -7.3 MeV). Measurements at accelerator facilities of the fast neutron response have been reported in the literature [5, 6, 7].
In the case of fusion plasma applications, a distinction should be made between the detection of Deuterium-Deuterium (DD) and Deuterium-Tritium (DT) neutrons. High resolution neutron spectrometry of 14 MeV neutrons is possible via the (n,α) reaction of neutrons on carbon nuclei, which is enabled for neutron energies above 6.17 MeV. Spectroscopic measurements for 2.5 MeV neutrons are possible only using the recoil spectrum of carbon nuclei from n+^{12}C scattering.
The main advantages of SDDs for neutron measurements in a tokamak environment are their compact dimensions, radiation hardness and insensitivity to magnetic fields, that make them of great interest, particularly in view of their possible use as detectors in a neutron camera with spectroscopy capabilities. Traditionally, high resolution neutron spectroscopy measurements have been performed with dedicated, non-compact detectors, such as TOFOR [8] or MPRu [9] at JET. Neutron spectroscopy observations have been used to derive an extended set of information on the plasma (temperature, rotational velocities, non-thermal components etc.), especially in discharges with external auxiliary heating [10, 11, 12, 13, 14, 15], and are therefore a key diagnostic in view of next step, high performance tokamak devices.
In this paper we present a selection of neutron spectroscopy measurements with a single crystal diamond detector performed at JET in the recent experimental campaigns, which demonstrate the capability of SDDs to provide information on the energy distribution of fast ions in the plasma. Prospects for future neutron measurements in JET deuterium-tritium plasmas using diamond detectors are finally addressed.

2. Instrumentation at JET

A diamond detector with a nominal active volume of 4.7×4.7 mm^2 (area) times 0.5 mm (thickness) and aluminum contacts (4.5 mm diameter) was installed at JET [16] in 2013 on a quasi-tangential, collimated line of sight defining an angle of 47 degrees with respect to the magnetic field at the plasma centre. The detector is housed in the beam dump of the MPRu spectrometer [9] (figure 1). 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 20 cm away from the detector and out of the neutron beam. After the first amplification stage, the signal is split in two lines by a Fan In Fan Out module. One of the two output signals is fed directly to a digitizer, with 1 Gsample/sec sampling frequency and 10 bits resolution. The other line goes through a second amplification stage made of a current amplifier, before being fed in the second channel of the same

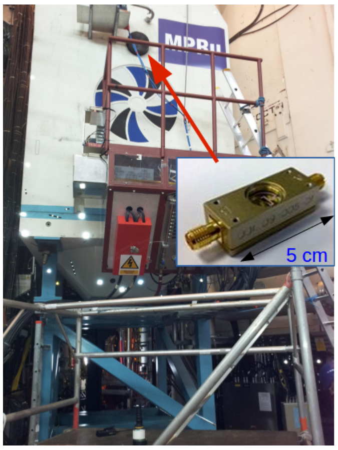


Figure 1: Photograph of the SDD installed at JET in the MPRu beam dump

digitizer. The reason for the two electronic chains is to enable measurements both of 2.5 MeV and, in the future, of 14 MeV neutrons from DD and DT plasmas, respectively. The expected amplitude of these two type of signals is different by a factor 20, due to the significantly different energy deposited by neutrons scattering on ^{12}C (2.5 MeV) or interacting with the detector via the ^{12}C(n,α)^{9}Be reaction (14 MeV). This motivates the need for two separate electronic chains.
An alpha particle source is available in front of the detector to provide the energy calibration. The typical energy resolution (FWHM/E) achieved in a calibration is 2.2% at 5.2 MeV, which is well below the expected Doppler broadening of the 14 MeV neutron spectrum from deuterium-tritium plasmas due to ion temperature effects (about 5%) .

3. Diamond measurements in plasmas heated by neutral beam injection

The SDD has been in operation at JET since the summer of 2013. An example of measured pulse height spectrum (PHS) is shown in figure 2 for discharge #84476 with 15 MW neutral beam injection applied for 6 seconds [17]. The PHS (integrated over the full discharge) has the characteristic box shape expected from the recoil of ^{12}C ions scattered by 2.5 MeV neutrons . The shoulder is at $E_d = 0.7$ MeV, as expected from the maximum energy deposited by back-scattering of 2.5 MeV neutrons on Carbon [18]. The broadening of the edge is a combination of the detector finite resolution and plasma kinematics.
The MCNP code was used to calculate the deposited energy spectrum of carbon nuclei from recoil due to elastic scattering with DD neutrons [19]. The model also includes the effect of neutron energy degradation due to interaction of the incoming neutrons with the MPRu instrument (scatter component in figure 2), as well as the production of background gamma-rays by neutron interaction with materials of the MPRu shielding (gamma). The energy spectrum of direct neutrons produced in the deuterium-deuterium reactions with neutral beam injection (direct) was simulated by the Monte Carlo code GENESIS [20, 21] and convolved with the calculated instrument response function. The result of a fit to the data is shown by the solid line in figure 2. Although several components have been included in the fit, there is only one overall normalization parameter, that gives the conversion from the number of neutrons emitted along the MPRu line of sight to that detected

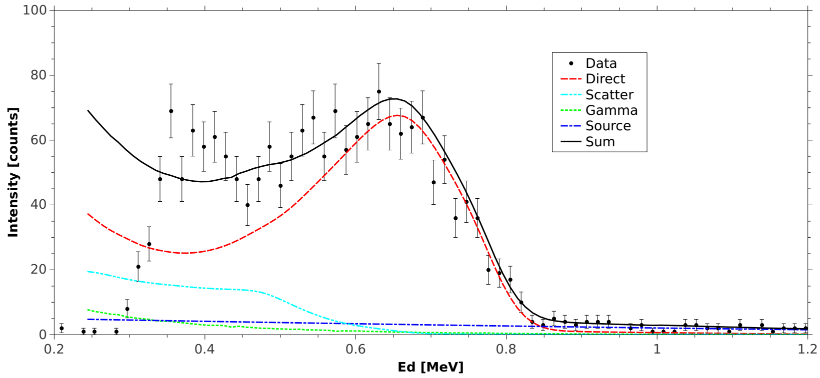


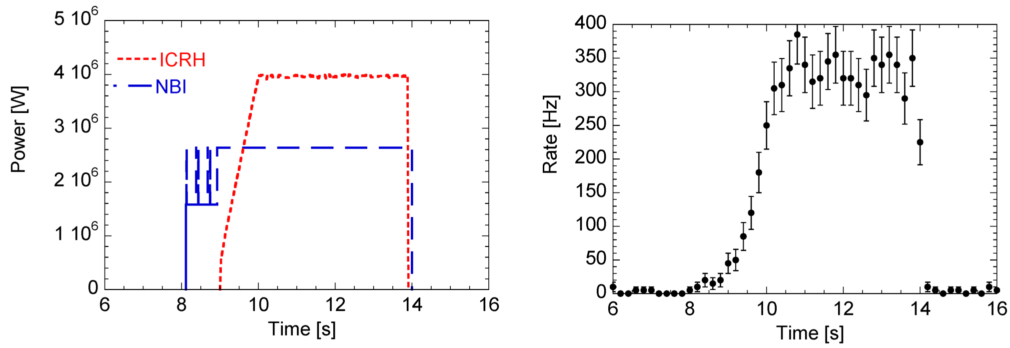
Figure 2: SDD spectrum measured at JET for discharge #84476 with neutral beam injection, as a function of the deposited energy E_d. A fit to the data is also shown. The components considered in the data analysis are direct neutrons from the plasma (direct), scattered neutrons (scatter) and background gamma-rays (gammas), as well as the background arising from the α calibration source (source).

by the SDD. The relative ratio between the different components was kept fixed and either given by MCNP (scatter and gamma components) or by the known counting rate from the calibration source in the measurement interval (source). A good agreement between measurements and simulations is observed (reduced Chi-square of 1.3) in the region E_d = 0.4 to 1.2 MeV. Data at lower energies were not included in the fit due to the need to use an experiment energy threshold in the measurements to remove low energy noise.

4. Diamond measurements in plasmas heated by radio-frequency

In a more recent experiment (summer 2014), the SDD was used to measure the neutron spectrum from radio-frequency heating tuned to the 3rd harmonic cyclotron frequency of deuterons injected by neutral beam in a deuterium plasma. Such scenario is known to be very effective at producing fast ions in the MeV range by exploitation of the synergistic effect between radio-frequency heating and the finite Larmor radius of the beam ions [12, 22]. As an example, figure 3(a) shows the time trace of the auxiliary heating used in discharge #86464. The addition of 4 MW of radio-frequency power on top of 2.5 MW of neutral beam injection produces an increase by a factor of about 10 in the neutron emission, as demonstrated by the counting rate of SDD in the time window 8 to 14 seconds (figure 3(b)).

Figure 4 shows the corresponding SDD spectrum integrated over the full discharge. Similarly to figure 2, we note the characteristic box shape spectrum from the recoil of ^{12}C nuclei. In this case, however, the falling edge of the spectrum extends well beyond E_d =0.7 MeV, revealing that the incoming neutron spectrum comprises energies exceeding 2.5 MeV, as expected in this type of discharges. A more detailed interpretation of the measured spectrum is possible by means of a one dimensional, “extended” Stix modeling of the distribution function of deuterium accelerated at the third harmonic, as in [12, 22]. From this input, we can use GENESIS to calculate the “direct” component of neutron emission expected in this scenario, which, as in figure 2, can be summed to the background components to fit the measured data. Again, a good agreement (reduced Chi-square



(a) (b)

Figure 3: a) Time trace of the auxiliary heating used in discharge #86464 with radio-frequency heating at the third harmonic on an injected beam of deuterium. b) Counting rate as a function of time measured by the SDD during the auxiliary heating phase.

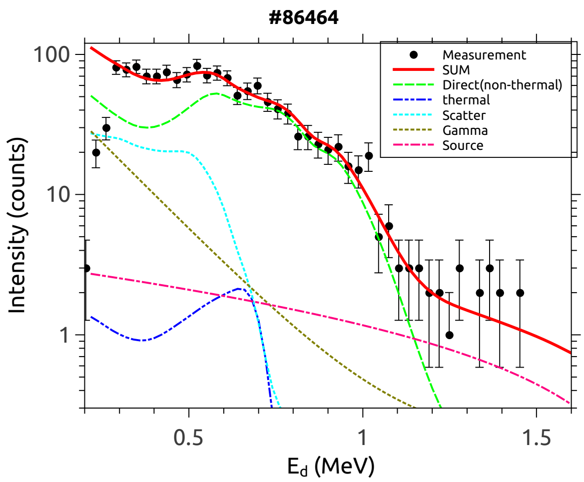


Figure 4: SDD spectrum measured at JET for discharge #86464 with radio-frequency heating at the third harmonic applied to an injected beam of deuterium. A fit of the spectrum using the same analysis procedure as for figure 2 is superimposed to the data

of 1.1) between model and measurements is found. A careful analysis of the measured spectrum reveals that parameters of the deuterium distribution function, such as the high energy cut-off of the distribution and the radio-frequency coupling constant, can be extracted from the SDD data. A detailed analysis of these discharges is presently in progress and will be published in separate papers [23, 24].

5. Conclusions and outlook

In this proceeding, neutron spectroscopy measurements performed at JET with single crystal diamond detectors (SDD) have been presented. Pulse height spectra recorded in plasmas heated by NBI and by a combination of NBI and radio-frequency have been illustrated and their shapes described in terms of the energy distribution of fast deuterons accelerated by the auxiliary heating.

In all cases it was found that the falling edge of the spectrum, besides featuring a non zero width due to the finite instrumental energy resolution, has an additional kinematic broadening, which can be related to the motion of the reactant deuterons.
Based on the successful operation of the SDD at JET described in this paper, efforts are presently ongoing to develop a matrix of SDDs so to boost the detection efficiency by a projected factor of about 10 [25]. This device, which will be placed about 1 meter behind the TOFOR neutron spectrometer at JET (sharing the same line of sight), is expected to be available from the next campaign and will be used for 2.5 MeV neutron emission measurements in high power plasmas, complementing TOFOR. In view of the next deuterium-tritium campaign, the SDD matrix will be the main spectrometer for 14 MeV neutron measurements along a vertical line of sight. In this type of plasmas, full advantage can be taken from the $^{12}C(n,\alpha)^{9}Be$ reaction between 14 MeV neutrons and the diamond detector. This results in a distinctive peak, whose spectral features can be used to extract components of the reactant energy distributions, complementing MPRu measurements of the neutron spectrum along a quasi-tangential line of sight.

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References

[1] A. Pietropaolo et al., Single-crystal diamond detector for time-resolved measurements of a pulsed fast-neutron beam, Europhysics Letters 92 (2010) 68003.

[2] A. Pietropaolo et al., Fission diamond detectors for fast-neutron ToF spectroscopy, Europhysics Letters 94 (2011) 62001.

[3] M. Rebai et al., Fission diamond detector tests at the ISIS spallation neutron source, Nuclear Physics B Proceedings Supplements 215, Issue 1, (2011), pp. 313-315.

[4] M. Rebai et al., Diamond detectors for fast neutron measurements at pulsed spallation sources, 2012 JINST 7 C05015

[5] A. Zimbal et al, Characterization of monoenergetic neutron reference fields with a high resolution diamond detector, Radiation Measurements 45 (2010) 1313

[6] M. Pillon et al, Experimental response functions of a single-crystal diamond detector for 5-20.5 MeV neutrons, Nuclear Instruments and Methods in Physics Research A 640 (2011) 185

[7] M. Rebai et al., Response of a single-crystal diamond detector to fast neutrons, Journal of Instrumentation 8.10 (2013): P10007.

[8] M. Gatu Johnson et al., The 2.5-MeV neutron time-of-flight spectrometer TOFOR for experiments at JET, Nucl. Instrum. Meth. A 591 (2008) 417

[9] G. Ericsson et al., Neutron emission spectroscopy at JET - Results from the magnetic proton recoil spectrometer, Review of Scientific Instruments 72 (2001) 759.

[10] M. Nocente et al. “Neutron spectroscopy measurements of tritium beam transport at JET” Nucl. Fusion 54 (2014) 104010

[11] C. Hellesen et al, Measurements of fast ions and their interactions with MHD activity using neutron emission spectroscopy, Nucl. Fusion vol. 50 (2010) p. 084006

[12] C. Hellesen et al., Fast ion distributions from third harmonic ICRF heating studied with neutron emission spectroscopy, Nucl. Fusion 53 (2013) 113009

[13] M. Gatu Johnson et al. "Neutron emission from beryllium reactions in JET deuterium plasmas with 3He minority." Nuclear fusion 50.4 (2010) 045005.

[14] M. Nocente, G. Gorini, J. Kallne and M. Tardocchi, Calculated neutron emission spectrum with knock-on effects for RF heated (3He)D plasmas, Nucl. Fus. vol. 51 (2011) p. 063011

[15] M. Tardocchi, M. Nocente and G. Gorini, Diagnosis of physical parameters of fast particles in high power fusion plasmas with high resolution neutron and gamma-ray spectroscopy, Plasma Phys. Control. Fusion 55 (2013) 074014

[16] F. Romanelli et al., Overview of JET results with the ITER-like wall, Nucl. Fusion vol. 53 104002

[17] C. Cazzaniga et al., Single crystal diamond detector measurements of deuterium-deuterium and deuterium-tritium neutrons in Joint European Torus fusion plasmas, Rev. Sci. Instrum. 85 (2014) 043506

[18] G. F. Knoll, Radiation Detection and Measurements, John Wiley and Sons, New York, NY, 1979

[19] MCNPX code website, http://mcnpx.lanl.gov/.

[20] M. Tardocchi et al., Spectral Broadening of Characteristic γ-Ray Emission Peaks from ^{12}C(3He,pγ)^{14}N Reactions in Fusion Plasmas, Phys. Rev. Letters 107, 205002 (2011)

[21] M. Nocente, “Neutron and gamma-ray emission spectroscopy as fast ion diagnostics in fusion plasmas”, PhD thesis, 2012, available online at https://boa.unimib.it/handle/10281/28397

[22] Nocente M. et al., High resolution gamma ray spectroscopy measurements of the fast ion energy distribution in JET ^{4}He plasmas, Nucl. Fusion 52, 063009 (2012)

[23] Eriksson J. et al., Diagnosing MeV range deuterons with neutron and gamma ray spectroscopy at JET, in preparation

[24] Nocente M. et al., Fast ion energy distribution from third harmonic radiofrequency heating measured with a single crystal diamond detector at JET, in preparation

[25] Cazzaniga C. et al., A diamond based neutron spectrometer for diagnostics of deuterium-tritium fusion plasmas, Rev. Sci. Instrum. 85 (2014) 11E101