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# First neutron spectroscopy measurements with a pixelated diamond detector at JET

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**Abstract.** A prototype Single Crystal Diamond Detector (SDD) was installed at JET in 2013 along an oblique line of sight and demonstrated the possibility to carry out neutron spectroscopy measurements with good energy resolution and detector stability in discharges heated by neutral beam injection and radio-frequency waves. Starting from these positive results, within the Vertical Neutron Spectrometer project of the Joint European Torus, we have developed a pixelated instrument consisting of a matrix of 12 independent SDDs, called the Diamond Vertical Neutron Spectrometer (DVNS), which boosts the detection efficiency of a single SDD by an order of magnitude..

In this paper we describe the main features of the DVNS, including the detector design, energy resolution and data acquisition system for on-line processing. Preliminary spectroscopy measurements of 2.5 MeV neutrons from the present deuterium plasmas at JET are finally presented.

## I. INTRODUCTION

Recent developments in the production of Single crystal Diamond Detectors (SDD), have resulted in important improvements in the detection capabilities of the diamond devices, in particular for fast neutron measurements include neutron emission monitors and neutron spectrometers [1,2,3,4,5]. The SDDs detectors offer high radiation hardness, compact size, fast response and insensitivity to magnetic field and gamma-ray background. These features make the SDDs interesting candidates for operation in the harsh environment of a high power tokamak such as the Joint European Torus (JET) [6]. In the SDDs, neutron detection is based on the collection of the of the electrons/holes pairs generated by the charged particles produced in the nuclear interactions between the incoming neutrons and the carbon nuclei of the diamond detector. In the fast neutron energy range several reactions can occur [7,8,9] . In particular, the detections of the 14 MeV neutrons produced by the nuclear fusion of the D-T nuclei, takes advantage from the $^{12}C(n,\alpha)^{9}Be$ reaction, which produces an α-particle and a $^{9}Be$ ion with a total energy equal to $E_\alpha+E_{Be}=E_n$-5.7MeV, where En is the energy of the impinging neutron [10]. The α particle releases its energy in the device, producing a peak in the recorded spectrum whose position and width depend on the incoming neutron energies. The detection of neutrons with energy below than 6 MeV (such as the 2.5 MeV neutrons produced by the D-D nuclear fusion reaction), can be performed using the elastic scattering of the neutrons on the carbon nucleus, generating recoiling $^{12}C$ nucleus carrying an energy up to 30% of the incoming neutron. The recoil $^{12}C$ nuclei release their energy in the device and this produces (for a mono-chromatic neutron beam) a spectrum presenting a continuous distribution ending at the maximum recoil energy transferred to the $^{12}C$ nuclei. A prototype SDD was installed at JET in 2013 and was used to successfully measure the 2.5 MeV neutron spectrum from deuterium plasmas [11]. Of particular relevance are recent experiments on radio frequency heating at the third ion cyclotron harmonic [12,13], where the prototype SDD was able to provide information comparable to those on non-compact, advanced spectrometers, such as TOFOR [14]. Motivated by these results, in this work we present the design, the installation and the first measurements in deuterium plasmas of the Diamond Vertical Neutron Spectrometer (DVNS). The instrument consists of a matrix of 12 SDDs pixel (each with separate HV power supply and read-out electronics) installed at JET on a collimated vertical line of sight at a distance of about 20 m from the plasma core and optimized for 14 MeV neutron measurements in the forthcoming JET deuterium-tritium campaign.

## II. DESIGN AND REALIZATION OF THE DIAMOND MATRIX

The 12 SDDs pixel matrix (shown in Figure 1) was designed and built at the CNR-ISM institute in Rome (Italy) [16,17, 18]. Each pixel of the matrix is a single crystal "electronic grade" diamond sample (dimensions of 4.5x4.5 $mm^2$ and 500 µm thick) with low concentration of impurities (boron concentration [B]<5ppb; nitrogen concentration [N]<1ppb) provided by Element Six Ltd. After the cleaning procedure of the diamonds, each pixel was provided with an ohmic contact obtained with the sputtering deposition technique. A multilayer metal contact was developed on the top and on the bottom surfaces of each sample. Finally, a thin gold layer was deposited on each contact to improve the weldability. The 12 pixels were then mounted on a dedicated 1 mm thick alumina Printed Circuit Board (PCB) by gluing the bottom surfaces of each diamond with a thin layer of conductive silver glue on the respective pixel pad hosted on the PCB. The top surfaces of the diamonds were wire-bonded on the ground plane. The PCB board was then mounted inside a custom made aluminium case equipped with 12 SMA (SubMiniature version A) connectors for pixel biasing and signal collection.

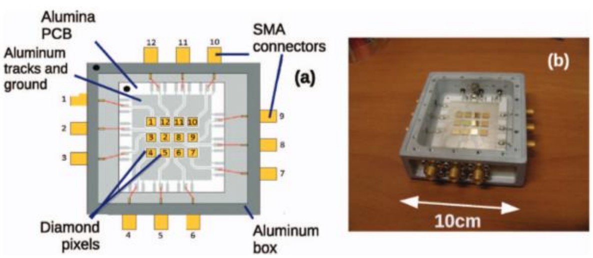


**Figure 1: The diamond matrix. (left) Scheme of the layout (right) A picture of the matrix.**

## III. EXPERIMENTAL SETUP

The diamond matrix was installed along a vertical line of sight at JET shared with the TOFOR neutron spectrometer and the GRS gamma-ray spectrometer [19,20]. The matrix support system was designed in order to reduce the amount of scattered neutrons (that can affect the TOFOR measurements) and the amount of gamma ray emitted due to the activation of the support materials (that can affect the GRS measurements). The support was then made of aluminum (low neutron interaction material) a set of stress analysis was carried out in order to reduce the total amount of material and the corresponding contribution to neutron energy degradation. Figure 2 shows the diamond matrix installed on the custom made support above the TOFOR structure.


**Figure 2: Experimental setup at JET. On the left: the diamond matrix system installed above the TOFOR neutron spectrometer. On the right: upper view of the diamond matrix with the 12 preamps.**

Each pixel of the matrix is read out using two separate electronic chains at the same time: one for 2.5 MeV neutrons from deuterium-deuterium reactions and one for 14 MeV neutrons from deuterium-tritium. Two independent electronic chains have been developed as 2.5 MeV neutrons deposit about 20 times less energy than 14 MeV neutrons, owing to their different interaction mechanisms. The first amplification stage (shared between the two electronic chains) is composed by twelve CIVIDEC C6 [21] fast pre-amplifiers (one for each pixel) placed about 15 cm away from the diamond matrix (shown in Figure 2), but outside of the neutron beam in order to avoid damage due to fast neutron irradiation. The twelve signals from the twelve preamplifiers are then transmitted to the diagnostic cubicle with twelve BNC cables (each with a length of about 15 meters). In the cubicle the signals are split by using a FIFO (Fan-In Fan-Out) device.A first set of signals is directly connected to the digitizer and is used for 14 MeV neutrons. The second set of signals, instead, is further amplified by twelve 20 dB fast current amplifier CIVIDEC C1 and is used to detect 2.5 MeV neutrons. The digitizer is composed by two 500 MHz, 14 bit CAEN V1730B VME module (16 channels each). The first module records the signals from the 2.5 MeV neutron chain, the second one records the signals from the 14 MeV neutron chain. Given the huge amount of data foreseen for the D-T campaign at JET (about 200 kHz of events per channel), a firmware (CAEN DPP-PSD) was installed in the digitizer modules to perform online signal processing. Figure 3 shows a schematic of the data acquisition system. The bias for each channel of the matrix is given by using a Wiener MPOD mini-crate equipped with two HV modules. The diamond matrix system is controlled by a Linux machine on which a custom made C++ code is implemented to control the DAQ and HV systems. The acquisition is triggered by the logic JET "pre"-signal (coming about 40 seconds before the discharge). When the pre signal arrives, the HV on each module is ramped up to 400 V and the DAQ modules are armed. The signals coming from the diamond matrix are then recorded for about 3 minutes from the pre signal. At the discharge end, the bias voltages are reversed for 2 minutes to avoid polarization effects [22]. Finally, all biases are set to 0 V waiting for the next discharge.

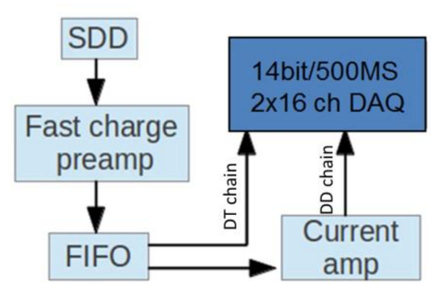


**Figure 3: Schematic of the read-out electronic chains at JET**

The calibration of each channel of the matrix was made in a dedicated experiment at neutron generators and in reported in [23]

## IV. NEUTRON MEASUREMENTS IN DEUTERIUM PLASMAS AT JET

The first neutrons measurements with the DVNS system were carried out for deuterium plasmas (2.5 MeV neutrons) from November 2015 during the JET C35 campaign. and compared with the simulation made using an MCNPX model. A series of discharges (#90170-#90177) was analyzed and compared to the simulations by combining an MCNP model of the instrument together with a calculation of the expected incoming neutron spectrum.. In the analyzed discharges plasma heating was obtained by Neutral Beam Injector (NBI) with an average power of about 17 MW. In these discharges deuterons injected by the NBI were accelerated up to 80 keV. The developed MCNP model was used to simulate the matrix response function to mono-energetic neutrons up to 5 MeV with an energy step of 20 keV. In the model the whole matrix geometry is taken into account and the simulations were performed by generating mono-energetic neutrons impinging on the front side of the detectors. The obtained response function of the diamond matrix was then convoluted with the expected neutron emission spectrum from the plasma. As a first attempt, we compared the measured data with the convolution of the matrix response function with mono-energetic neutrons at 2.45 MeV. As one can see from the green line of Figure 4, the results of this simulation do not match the data, with discrepancies at low and high deposited energies. A more detailed model was then used to improve the agreement of the measured data with the simulations. The response function of the diamonds matrix was convoluted with the neutron spectrum calculated by the MonteCarlo GENESIS code [24,25], which allows determining the neutron emission spectrum starting from arbitrary reactant distribution functions. The simulation included neutron emission components from the thermal population (thermal component), the beam deuterons interacting with thermal ions (beam-plasma component) and fusion reactions among deuterons of the beam (beam-beam component) [26]. The sum of these three components is shown by the yellow line of Figure 4. We now find a good agreement with the measured data at high energies, but there is still a significant excess of events in the low energy part of the spectrum and that is not described by the yellow curve. This arises from neutron scattering in their path from the plasma to the spectrometer. When this further process is included (black curve in Figure 4) , a good agreement between data and the simulation is established also at low deposited energies (red curve). During the JET campaign C36, in addition to plasmas with only NBI heating, some sessions used a combination of NBI and RF heating. A series of neutron spectra was recorded by the DVNS system during these discharges (#90188-#90202) and the results (red squares), together with the neutron spectra recorded with NBI only (black circles), are shown in Figure 5. For these plasmas we find an increased energy tail in the spectrum compared to that observed in plasmas heated by NBI only. This increment is interpreted as due to the acceleration of the deuterons up to few MeV from the synergetic effect between fast ions and RF waves, as expected in these discharges [13,27]. A quantitative analysis of this scenario is on-going and will be published in a future paper.

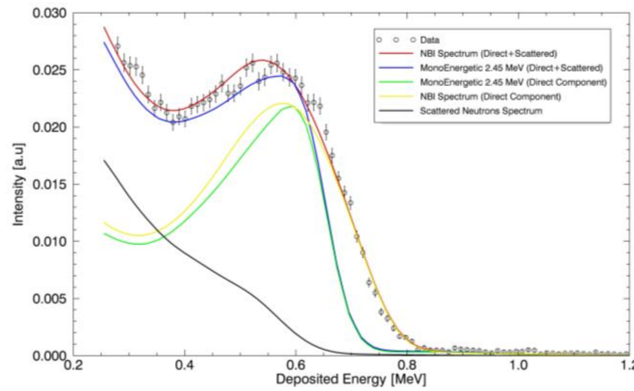


**Figure 4: Sum of the measured data recorded during the plasma dischargers from number 90170 to 90177 compared with: response to 2.45 MeV mono-energetic neutrons (green line), response to the calculated neutron spectrum emitted from the plasma with NBI heating (yellow line), response to the calculated scattered neutrons spectrum (black line), sum of the mono-energetic and scattered spectrum (blue line) and sum of the NBI and the scattered spectrum (red line).**

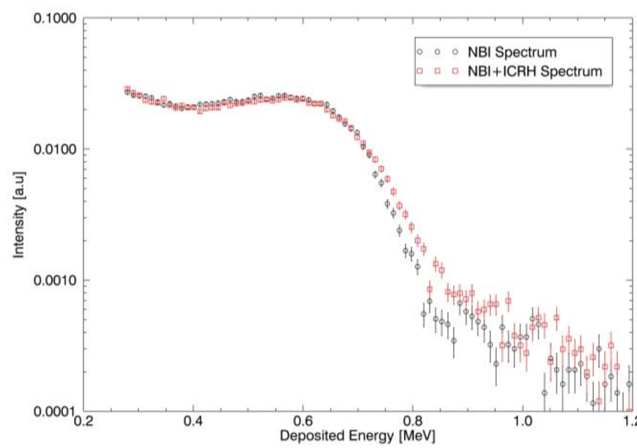


**Figure 5: Comparison of the sum of the recoded spectrum with the only NBI plasma heating (black circles) with the sum of the recorded spectrum with both NBI and RF plasma heating (red squares).**

## V. CONCLUSIONS AND FUTURE WORK

The DVNS (Diamond Vertical Spectrometer) system was successfully developed, constructed and installed ad JET in October 2015 and is in operation since November 2015. First neutron spectra measured by the DVNS system in JET deuterium plasma discharges with NBI heating are well reproduced by combining neutron emission models with the instrument response function. Observations in deuterium plasmas with combined NBI and RF heating reveal an excess of events at high deposited energies, which is in qualitative agreement with expectations for this scenario. The results achieved so far demonstrate the successful operation of the DVNS in deuterium plasmas and open up to future measurements of 14 MeV neutrons in deuterium-tritium.

## VI. ACKNOWLEDGMENT

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