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Single-crystal Diamond Detector for DT and DD plasmas diagnostic

M. Rebai(1)(*), C. Cazzaniga(2), M. Tardocchi(3), G. Grosso(3), G. Croci(1),
E. Perelli Cippo(3), P. Calvani(4), M. Girolami(4), D. M. Trucchi(4)
and G. Gorini(2)

(1) *University of Milano Bicocca - Piazza della Scienza 3, 20126 Milano, Italy*
(2) *STFC, Rutherford Appleton Laboratory - Didcot, OX11 0QX, UK*
(3) *IFP-CNR - Via Cozzi 53, 20125 Milano, Italy*
(4) *CNR-IMIP - Via Salaria, Monterotondo Scalo (RM), Italy*

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Summary. — Single-crystal Diamond Detectors (SDD) are good candidates as high-energy neutron detectors in the extreme conditions of the next generation thermonuclear fusion facilities like the ITER experiment, due to their high radiation hardness, fast response time and small size. Neutron detection in SDDs is based on the collection of electron-hole pairs produced by charged particles generated by neutron interaction on ^{12}C. In this work the SDD response to neutrons with energies between 2.8 and 3.8 MeV was determined at the Legnaro CN accelerator at the INFN Laboratories in Legnaro (PD, Italy). This work is relevant for the characterization of SDDs response functions, which are key points for Deuterium-Deuterium and Deuterium-Tritium plasma diagnostic.

1. – Introduction

Diamond Detectors, due to their high radiation hardness, fast response time and small size, are good candidates as fast neutron detectors in those environments where the high neutron flux is an issue, such as in the thermonuclear fusion environment, *i.e.* the ITER experiment. By measuring the neutrons emitted from the plasma much information can be obtained on the plasma itself, *e.g.* density and temperature. For example, in a Deuterium-Tritium (DT) plasma, the 14 MeV neutron peak width would be proportional to the plasma temperature [1]. For a diamond-based diagnostic the spectroscopic channel which can be used for 14 MeV neutrons measurements in fusion

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(*) E-mail: `marica.rebai@mib.infn.it`

plasmas is the ^{12}C(n,α)^{9}Be reaction. The possibility of using the SDD prototype in fusion environments for spectroscopic neutron measurements was successfully investigated with Deuterium-Deuterium (DD) plasmas at JET [2].

In order to fully characterize the SDD response to neutrons a single pixel prototype was tested with 14 MeV neutrons at the FNG neutron source (ENEA-Frascati, Italy) [3, 4]. Here, the characterization of the SDD prototype with neutrons with energies from 2.8 MeV to 3.8 MeV will be described.

2. – Experimental set-up

2·1. *The SDD detector.* – Neutron detection in SDDs is based on the collection of electrons and holes generated in the detector active volume (13 eV are needed to produce an *e-h* pair) by charged particles produced via neutron-induced nuclear reactions on ^{12}C. The main reactions occurring in carbon are:

- the n-α reaction: ^{12}C(n,α)^{9}Be ($Q_{\text{value}} = -5.7\,\text{MeV}$, $E_{thr} = 6.17\,\text{MeV}$);
- the elastic neutron scattering channel: ^{12}C(n,n$'$)^{12}C;
- the n-3α reaction (carbon breakup): ^{12}C(n,n$'$)3α ($Q_{\text{value}} = -7.23\,\text{MeV}$, $E_{thr} = 7\,\text{MeV}$).

The first reaction, due to the reaction kinematics, represents the spectroscopic channel: in this case, the deposited energy, ideally, equals the incoming neutron minus the reaction Q-value. The other two give rise to a continuum up to the energy of the ^{12}C(n,n$'$)3α reaction shoulder (E_n–Q_{value}). For neutrons with an energy lower than 7 MeV, such as neutron from DD plasmas, the elastic channel is the only reaction channel which can occur.

The detector was designed and built at the CNR-IFP in Milan and at the CNR-ISM institute in Rome (Italy) [5-12]. The SDD is made of a single-crystal diamond sample ($4.5 \times 4.5 \times 0.5\,\text{mm}^3$) with boron concentration $[B] < 5\,\text{ppb}$ and nitrogen concentration $[N] < 1\,\text{ppb}$), provided by Element Six Ltd. [13]. Ohmic contacts were obtained on top and bottom surfaces of the sample by subsequent sputtering depositions of a multilayer metal structure (patent pending), followed by a final gold layer deposition, in order to improve weldability with microwires and to prevent oxidation of the underlying structure. The contact thickness is 200 nm with a lateral dimension of $4.2 \times 4.2\,\text{mm}^2$.

A dedicated 1 mm thick alumina Printed Circuit Board (PCB) was designed and fabricated; the bottom surface of the diamond sample was glued with a thin layer of conductive silver paste on the pad, whereas top surface were wire-bonded (by means of 25 μm thick Al/Si wires) on the ground plane. The alumina PCB is housed inside a properly designed and developed aluminum metal case in order to shield it from electromagnetic interference and to give the detector the mechanical resistance. The case is equipped with a SMA connector for detector biasing and signal collecting, on the top of it an hole was performed in order to allow the alpha particle injection.

2·2. *The electronic chain.* – The SDD was coupled though a 5 cm RG62 cable to a CIVIDEC c6 fast charge preamplifier [14], which has a rise time of 3.5 ns and a shaping time of 25 ns. A CAEN HV Module NDT1470 was used to bias the detector [15]. A bias voltage of +400 V was applied, giving an electric field of 0.8 V/μm in the diamond bulk. The preamplifier output was fed into a C1 broadband amplifier in order to enhance the height of the signal of about a factor 10: the signal is then fed into a waveform digitizer

Table I. – *Neutron energies calculated analytically and used for SDD neutron calibration.*

Measure	Proton Energy (MeV)	Angle (degrees)	Neutron energy (MeV)
10	5	0	3.3
12	4.5	0	2.8
17	5.5	0	3.8

CAEN DT5730 (14 bit and 500 MS/s sampling rate). The digitizer is equipped with a software able to process on-line the data and sort them into an energy histogram. The choice of the electronic chain was made in order to combine a good energy resolution ($< 4\%$) with the possibility to measure the neutron flux at high rates (>1 MHz) [16,17].

2˙3. *The beam.* – The measurements were performed at the Legnaro National Laboratories on April 2015. Neutrons were produced by protons impinging on a ^{7}LiF target. Proton beam energy was in the range (4.5–5.5 MeV) and the expected neutron energies at 0 degrees are reported in table I. The distance between the SDD and the target was about 4 cm in order to maximize the count rate.

3. – Results

The most important result achieved during the experiment is the evaluation of the SDD response to quasi-monoenergetic neutrons. This response can be described by analyzing the spectra in fig. 1. The plot on the left shows the Pulse Height Spectra obtained by making the histogram from data collected by the digitizer: three neutron energies are here reported. The x-axis was calibrated by using an ^{241}Am α emitter, which emits α particles of 5.5 MeV. The y-axis is reported in counts/second/bin. The bin width is 50 eV, while the data acquisition time is 6200 s, 7500 s and 8550 s for measure 10, 12 and 17, respectively. As said, the only interaction channel between neutrons and ^{12}C atoms is the elastic recoil: through this reaction the energy deposited into the detector E_d is equal to $0.298 \cdot \cos^2\theta * E_n$, where θ is the recoiling angle. The energy deposited reaches a maximum when the recoiling angle is zero, therefore by evaluating the position of the elastic shoulder the neutron energy can be measured. The three shoulders were fitted (fig. 1 right) with a step function convoluted with a Gaussian in order to evaluate the energy deposited into the detector and the energy resolution. In measure 17, red line, the shoulder position is at $E_d = 1.15$ MeV, which gives a neutron energy of $E_n = 3.86$ MeV,

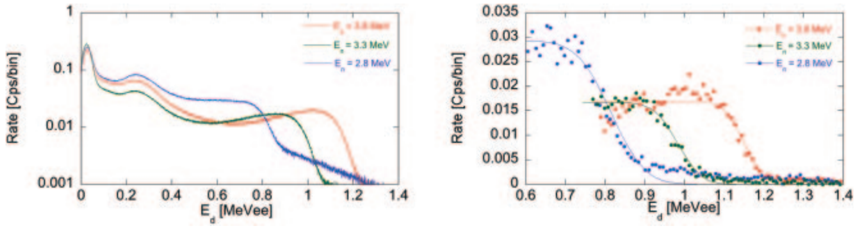

Fig. 1. – Left: Pulse Height spectra for neutrons of 2.8, 3.3 and 3.8 MeV normalized respect to the acquisition time: 6200 s, 7500 s and 8550 s, respectively; the Energy Bin Width is 50 eV. On the right the shoulders fit with a step function convoluted with a Gaussian is shown.

with a deviation standard of 40 keV. In runs 10 (green line) and 12 (blue line) we measured a shoulder position of 0.98 MeV and 0.81 MeV giving neutron energies of 3.29 MeV and 2.71 MeV, respectively. The agreement between the measured neutron energy and the expected one, shown in table I, is very good. The energy resolution measured at neutron energies of 2.8 MeV, 3.3 MeV and 3.8 is 5.6%, 3.4% and 2.4%, respectively: such a result is very good and matches the requirements for being a plasma diagnostic ($< 5\%$).

4. – Conclusions

This work is the starting point for a complete characterization of SDDs in the energy range 0–20 MeV which is a key point for Deuterium-Deuterium and Deuterium-Tritium plasma diagnostic with Single-crystal Diamond Detectors. A matrix of 12 SDD pixels has been installed at JET (Joint European Thorus) at Culham, GB [18] to be a plasma diagnostic in the next DD campaign in 2015 and in the DT campaign planned for 2018.

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