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Capabilities of a Diamond Detector matrix for neutron spectroscopy measurements at JET*

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Single-crystal Diamond Detectors (SDDs) feature high radiation hardness, fast response and compact size. This makes SDDs ideal candidates for fast neutron detectors in environment where high neutron flux is an issue such as the next generation burning plasmas experiments. Neutron detection in SDD is based on the collection of electron-hole pairs produced by charged particles generated by neutron interaction with ^{12}C nuclei. For neutron energies above about 7 MeV neutron spectroscopy is possible by measuring the deposited energy into the detector via the reaction ^{12}C(n,α)^{9}Be. This is indeed the cases of SDD measurements of 14 MeV neutrons of DT plasmas. A single pixel SDD (4.5x4.5x0.5 mm^3) prototype was installed at JET in 2013 and the achieved results allowed to assess also the neutron spectroscopic capability of deuterium plasmas. A 12-pixels SDD matrix has been recently realized and will be installed in 2015 at JET for DT plasmas as part of the Vertical Neutron Spectrometer project.

In this paper calibration of the SDD matrix with alpha particles in the laboratory and 14 MeV neutrons performed at the ENEA Frascati Neutron Generator will be presented. These calibrations have been performed with a fast charge preamplifier combined to a fast digital data acquisition, which allows for neutron spectroscopy measurements with simultaneously high energy resolution and high count rate capability. Both requirements are essential for neutron spectroscopy of high power fusion plasmas. The calibrations results achieved extrapolate favourably in view of future neutron spectroscopy measurements at JET using diamond detectors.

* See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia**.**

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[1] Speaker

1. Introduction

Single-crystal Diamond Detectors (SDDs) offer advantages such as high radiation hardness, fast response time and low sensitivity to magnetic fields which make them ideal candidates for fast neutron detectors in environments where high neutron flux is an issue, such as the next generation burning plasmas experiments [1]. Furthermore, their small size can be highly appreciated in those facilities for which a compact device is required. Neutron detection in SDD is based on the collection of electron-hole pairs produced by charge particles generated by neutron interaction with ^{12}C carbon nuclei in the detector. The main nuclear reaction channels occurring are:

- elastic and inelastic scattering $^{12}C(n,n')^{12}C$;
- n-3α reaction (carbon breakup) $^{12}C(n,n')3\alpha$ (Q_{value}=7.23 MeV);
- n-α reaction $^{12}C(n,\alpha)^{9}Be$ (Q_{value}=5.7 MeV).

The latter reaction $^{12}C(n,\alpha)^{9}Be$ is the selected one for 14 MeV neutron spectroscopy measurements from a Deuterium-Tritium (DT) plasma [2]. In this case, in fact, the resulting deposited energy in the detector corresponds to the incoming neutron energy minus the reaction Q-value. A peak centred at $E \approx 8.3$ MeV which can be directly related to the incoming neutron spectrum. From the 14 MeV neutron spectrum information on plasma parameters can be extracted such as the ion temperature and the thermal/non thermal neutron emission ratio [3]. Furthermore, the remaining reaction channels give rise to a continuum in the pulse height spectrum. In particular the elastic and inelastic scattering contribute to the characteristic broad response function typical of compact neutron detectors which are based on recoil ion scattering and can still in principle be exploited for a basic neutron spectroscopy.

Previous tests with a single pixel prototype SDD have already shown excellent performances in neutron spectroscopy, such as a good energy resolution when a fast digital spectroscopic chain is used, a high count rate capability and the possibility to perform spatially resolved measurements of a fast neutron flux [4]. A single pixel SDD (4.5x4.5x0.5 mm^3) prototype was installed at JET in 2013 and the achieved results allowed to assess the 2.5 MeV neutron spectroscopic capability of Deuterium-Deuterium plasmas [5]. A new system based on a 12-pixels SDD matrix has been recently realized. Each pixel is equipped with independent high voltage supply and read-out electronics ad hoc built to combine the high counting rate capability with the good energy resolution. The matrix will be installed in 2015 at JET on a collimated vertical line of sight, for Deuterium-Tritium campaign as part of the Vertical Neutron Spectrometer project.

In this work the design and realization of the diamond system composed of 12 pixels SDD matrix and dedicated electronics will be presented. The use of dedicated fast charge preamplifier combined to a fast digital data acquisition has allowed for the first time to perform neutron spectroscopy measurements with simultaneously high energy resolution (<3% at 14 MeV) and high count rate capability (>1 MHz). Both requirements are essential for neutron spectroscopy of high power fusion plasmas. Calibration results with alpha particles in the laboratory and 14 MeV neutrons performed at the Frascati Neutron Generator will be presented.

1. Experimental setup description

1.1 Design and realization of the 12-pixel SDD matrix

A 12 pixel matrix was designed as neutron spectrometer and built at the CNR-ISM institute in Rome (Italy) [6-9]. Each pixel is made of a single-crystal diamond sample (4.5 x 4.5 mm^2 , 500 µm thick, with a boron concentration [B] < 5 ppb and nitrogen concentration [N] < 1 ppb), provided by Element Six Ltd [10]. In order to remove any organic and metallic impurity, each crystal was cleaned for 30 s in a boiling mixture (1:1:1) of nitric, sulphuric and perchloric acid, then rinsed in deionized water. Ohmic contacts were obtained on top and bottom surfaces by subsequent sputtering deposition of a multilayer metal structure (patent pending), followed by a final gold layer deposition. A dedicated 1 mm-thick alumina Printed Circuit Board (PCB) was designed and fabricated for the 12 pixel matrix. The bottom surface of the diamonds were glue with a thin layer of conductive silver paste on their respective pixel pad, whereas their top surfaces were wire-bonded on the ground plane [10]. Aimed at reducing cross-talk effects, each pixel pad and each signal track were completely surrounding by the ground plane. All pads and signal tracks, as well as the ground plane, are aluminum-made to minimize the metal activation by neutrons. A properly aluminum metal case has been designed and realized in order to house in the alumina PCB and to shield it from electromagnetic interference. Finally, the case was equipped with 12 SMA (SubMiniature version A) connectors for pixel biasing and signal collecting, and the top is provided with 12 holes (one per each pixel) to allow alpha particles to reach the diamonds for calibration measurements (the holes operate like pinhole collimators).

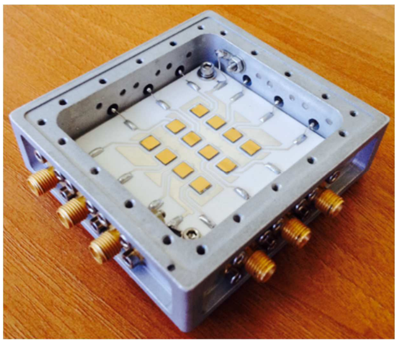

Figure 1. Picture of the 12-pixel diamond matrix without the top.

1.2 The acquisition chain

All the experiments present in this work, have been performed with the same digital acquisition chain, which will be used at JET.

Each pixel was equipped with an own independent read-out electronic, as well as an independent high voltage supply. The diamonds were powered with a bias voltage of +400 V provided by a CAEN HV module NDT1470 (4 channels) and an ISEG HV module EBS 8005 (8 channels) for the firsts four and the remaining pixels, respectively. Furthermore, each diamond was coupled through a 10 cm RG62 cable to a CIVIDEC C6 fast charge preamplifier [12], which has a rise time equal to 3.5 ns and a Gaussian pulse shape with a FWHM of 10 ns [13]. The fast preamplifier has been used in order to meet high rate measurement requirements. The downside of using a fast charge preamplifier is a degraded energy resolution compared to what can be achieved with conventional spectroscopic preamplifiers [13], which however are too slow for usage in high rate applications. Via 15 m long cables the signals from the preamplifiers were fed into a 16 channel waveform digitizer CAEN module V1730B (14-bit, 500 MS/s) which was used to record the signals. The digitizer is equipped with a CAEN software able to perform on-line measurements of the pulse area, by integrating each signal in a user defined gate. In this way it was possible to build and store the deposited energy spectra.

1.3 Alpha particle measurements

In order to characterize and calibrate each single pixel with its own electronic chain, alpha particle measurements with a ^{241}Am source were performed in laboratory at the Istituto di Fisica del Plasma in Milan. At first, measurements were carried out in a vacuum chamber so as to decrease the alpha particle energy straggling and to have a more accurate calibration, then they were done again at atmospheric pressure. These second measurements were aimed to evaluate any future calibration performed in those environments where a vacuum chamber cannot be used, such as on the vertical line of sight of JET. Each pixel was coupled to the ^{241}Am source thanks to the 12 holes and the acquisition was performed pixel-by-pixel by using the electronic chain already described.

1.4 Measurements of 14 MeV neutrons at Frascati Neutron Generator

Measurements of 14 MeV neutrons were performed at the ENEA Frascati Neutron Generator (FNG) aimed to evaluate the matrix detector response. In this facility, the deuterium ions are accelerated and sent onto a tritiated-titanium target so that neutrons production occurs by deuterium-tritium reaction. The device was placed at 90° respect to the incoming deuterium beam at a distance of 22 cm from the target. A typical single pulse of a 14 MeV neutron recorded by a diamond pixel is shown in figure 2. It can be appreciated that the FWHM of the pulse is about 10 ns which is a necessary condition to be able to perform measurements at very high counting rates.

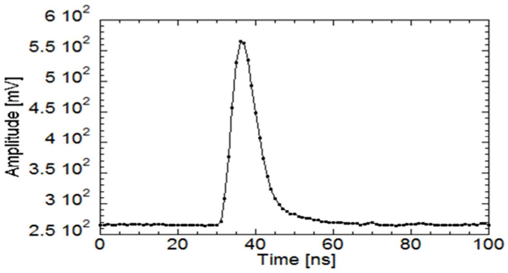

Figure 2: A single recorded waveform for a 14 MeV neutron is shown.

1. Results

Calibration measurements have been performed per each pixel with alpha particles both in vacuum and in air at atmospheric pressure. For the latter set-up, alpha-particle energy loss in air has been evaluated by SRIM code [14], which calculate the stopping and range of ions into matter. At first, each recorded spectrum was fitted by a Gaussian function in order to estimate its FWHM and peak position and then it was calibrated. Energy Resolution (FWHM/Peak Position) is plotted in figure 3. The mean value of the energy resolution for the recorded peaks during the measurements in vacuum is 1.74 % (96 KeV in terms of FWHM) with a standard deviation of

0.08 %. Figure 4, furthermore, shows the ratio of the peak position in vacuum to the peak position in air.

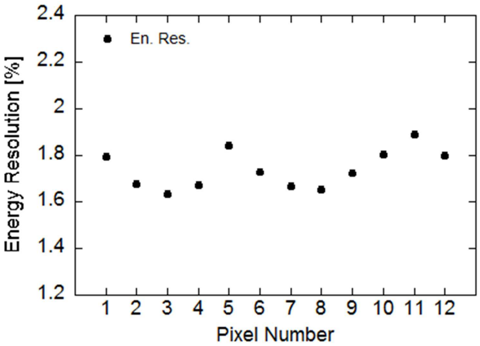

Figure 3: Energy Resolution dispersion graph for measurements in vacuum. Errors are not shown because of the same magnitude of the black dots.

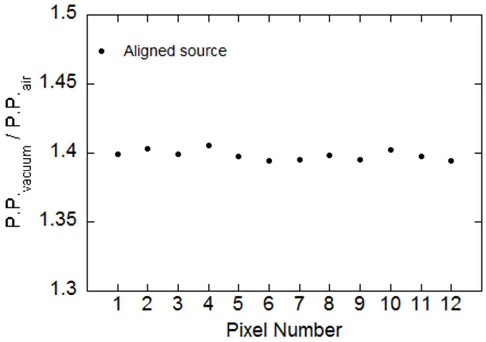

Figure 4: Ratio of the peak position in vacuum to the peak position in air. The blue dot represents the measurement with the non-aligned source.

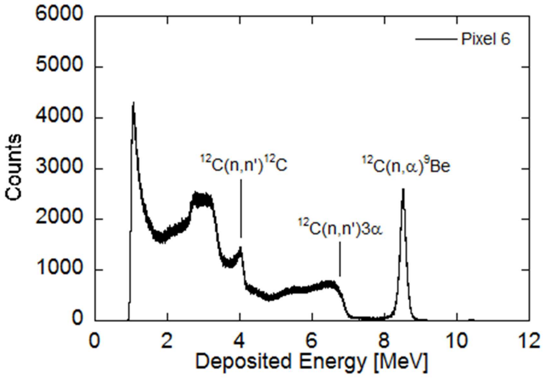

Figure 5: Deposited energy spectrum of 14 MeV neutrons for Pixel 6.

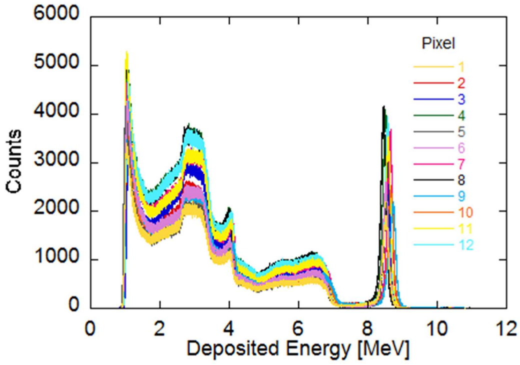

Figure 6: Pulse height spectra measured for each pixel at the FNG with14 MeV neutrons.

The recorded spectra at Frascati Neutron Generator were calibrated with the alpha calibration spectra. The peaks due to the n-α reaction were analyzed by a Gaussian fit in order to find the FWHM and peaks positions. The mean value of the calculated energy resolution for the 12 peaks is 191 KeV (in terms of FWHM) with a standard deviation of 17 KeV. Instead, the contribution of the beam energy width is estimated to be about 150 KeV. Therefore, we can assert that the intrinsic energy resolution of the detector is even less than 191 KeV. Figure 5 shows a single calibrated spectrum, whereas the figure 6 shows the calibrated pulse height spectra measured for each pixel of the matrix detector. In the latter graph, it is possible to notice a small shift of the (n,α) peak between different pixels. This is because the 12 pixels, which are in different positions, detect neutrons of different energy depending on their emission angle. Thanks to these measurements we can infer that all the pixel detectors feature a similar response in term of gain and energy resolution.

2. Conclusions

The response of a Single-crystal Diamond Detector matrix was measured with 14 MeV neutrons and alpha particles obtaining a mean energy resolution of 96 KeV and less than 191 KeV for 5.486 MeV alphas and 14 MeV neutrons, respectively. Furthermore as shown in the Rebai’s paper [11], an equal response of each pixel to radiation was observed also for different electronic chains and for neutron measurements. The detection system described in this work will allow for the first time to perform neutron spectroscopy measurements with simultaneously high energy resolution and high count rate capability, both required for neutron spectroscopy of high power fusion plasmas.

3. Acknowledgments

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