EUROFUSION WPJET4-PR(16) 15266

M Rebai et al.

Response function of single crystal synthetic diamond detectors to 1-5 MeV neutrons for spectroscopy of D plasmas

Preprint of Paper to be submitted for publication in
21st Topical Conference on High Temperature Plasma
Diagnostics 2016

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This document is intended for publication in the open literature. It is made available on the clear understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original when applicable, or without the consent of the Publications Officer, EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK or e-mail Publications.Officer@euro-fusion.org

Enquiries about Copyright and reproduction should be addressed to the Publications Officer, EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK or e-mail Publications.Officer@euro-fusion.org

The contents of this preprint and all other EUROfusion Preprints, Reports and Conference Papers are available to view online free at http://www.euro-fusionscipub.org. This site has full search facilities and e-mail alert options. In the JET specific papers the diagrams contained within the PDFs on this site are hyperlinked

Response function of single crystal synthetic diamond detectors to 1-4 MeV neutrons for spectroscopy of D plasmas

M. Rebai[1,2], L. Giacomelli[2], A. Milocco[1,3], M. Nocente[1,2], D. Rigamonti[2], M. Tardocchi[2], F. Camera[4], C. Cazzaniga[5,2], Z. J. Chen[6], T. F. Du[6], T. S. Fan[6], A. Giaz[4], Z. M. Hu[6], T. Marchi[7], X. Y. Peng[6], G. Gorini[1,2] and JET Contributors[8*]

[1]*University of Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[2]*Istituto di Fisica del Plasma "P. Caldirola", CNR, Milano, Italy*
[3]CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom
[4]*INFN Milano, Via Celoria 16, 20133 Milano, Italy.*
[5]*STFC, Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom*
[6]*School of Physics, State Key Lab of Nuclear Physics and Technology, Peking University Beijing, China*
[7]*INFN Laboratori Nazionali di Legnaro, Viale dell'Università, 2 - 35020 Legnaro (PD), Italy*
[8]*EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK*
[*]*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)

A Single-crystal Diamond Detector (SDD) prototype was installed at JET in 2013 and the achieved results have shown its spectroscopic capability of measuring 2.5 MeV neutrons from deuterium plasmas. This paper presents measurements of the SDD response function to monoenergetic neutrons, which is a key point for the development of a neutron spectrometer based on SDDs and compares them with Monte Carlo simulations. The analysis procedure allows for a good reconstruction of the experimental results. The good pulse height energy resolution (equivalent FWHM of 80 keV at 2.5 MeV)**,** gain stability, insensitivity to magnetic field and compact size make SDDs attractive as compact neutron spectrometers of high flux D plasmas, such as for instance those needed for the ITER neutron camera.

I. INTRODUCTION

Single crystal Diamond Detectors (SDDs) have been exploited mainly as neutron flux monitors in high power fusion devices, given their radiation hardness, high energy resolution, insensitivity to magnetic field and compact size [ref pillon-angelone][1][2][3]. Recently it has been shown that SDDs can play a role as compact neutron spectrometers in high neutron flux environments and where there is limited space, e.g. neutron cameras [ref nostre] [4][5]. 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 [6]. For neutron energies above about 6 MeV, neutron spectroscopy is possible by measuring the deposited energies of the products of the reaction $^{12}C(n,\alpha)^{9}Be$ [7]. This is the case of neutron spectroscopy of 14 MeV neutrons from DT plasmas [8] where very high energy resolution have been demonstrated [9]. For energies below 6 MeV, the possibility of performing neutron spectroscopy via elastic and inelastic scattering with carbon nuclei has been explored. In this case the SSD response has a characteristic flat broad response and the detector can be exploited as counter and moderate energy resolution neutron spectrometer. An SDD prototype was installed at JET in 2013 [10][11] and the achieved results have successfully shown for the first time its spectroscopic capability of measuring 2.5 MeV neutrons from deuterium plasmas

A key point for the development of a neutron spectrometer based on SDDs is the measurement of the detector response function to quasi-monoenergetic neutrons. In this paper we report the measurement performed at the Heavy Ion Physics department at the Peking University (China) **Error! Reference source not found.**[13] and at the CN facility at the INFN-LNL (Laboratori Nazionali di Legnaro) [14] in Legnaro (Padua, Italy), where the diamond response function was measured for neutrons in the energy range 1-4 MeV.

II. EXPERIMENTAL SET UP

The SDD used in these measurements was built at the CNR-ISM [16][17] institute in Rome (Italy), and consists of a single-crystal diamond sample [18](4.5 x 4.5 x 0.5 mm^3) which has on the top and bottom surfaces Ohmic contacts obtained 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 [19]. The detector (see Figure 1) was coupled though a 5cm RG62 cable to a fast charge preamplifier (rise time of 3.5 ns, shaping time of 25 ns, gain of 6mV/fC, bandwidth of 100 MHz) [20]. A CAEN HV Module NDT1470 [21] was used to bias the detector at +400V, giving an electric field in the bulk of 0.8 V/um. The preamplifier output was fed into a second amplification stage, a broadband amplifier in order to increase the signal of 20dB. The output was then connected to a waveform digitizer CAEN DT5730 (14 bit and 500 MS/s sampling rate) equipped with a software able to process on-line the data and sort them into an pulse charge histogram.

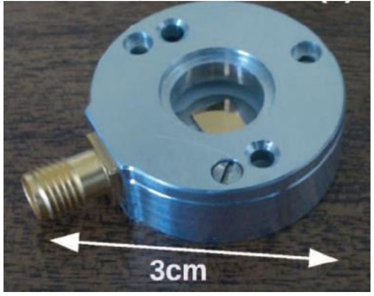

Figure 1: Picture of the Diamond Detector used for the measurement at INFN_LNL.

The measurements were performed at the Heavy Ion Physics Department at the Peking University and at the CN facility at the INFN-LNL. In the first facility a proton beam of 3.3 MeV accelerated by a Van-der-Graff was delivered on a T-Ti target (500 ug/cm^2), giving neutrons of 1.0 MeV at 95 ^{o}, 1.98 MeV at 45^o and of 2.47 MeV at 12^o. The second facility is located in Padua and uses a Van-der-Graff which accelerates protons on a ^{7}LiF target (700 ug/cm^2). This reaction gives neutron of 2.8, 3.32, 3.82 MeV, by using protons of 4.5, 5, 5.5 MeV.

Typical measured pulse height spectra (see Figure 2) feature the characteristic broad response related to the scattering recoil on ^{12}C.

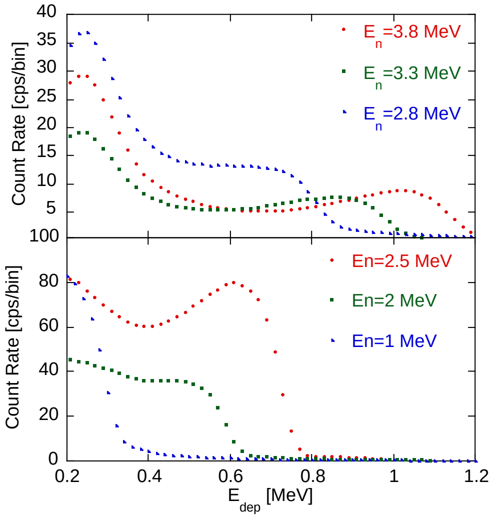

Figure 2: Pulse height spectra of a SDD irradiated at the INFN-LNL facility (top) and at the Pecking University (bottom) The incoming monoenergetic neutron energies are indicated in the legend. Statistical error bars are of the same size of the point sizes.

The measured pulse height spectra have been calibrated by using a triple alpha source (^{241}Am, ^{244}Cm, ^{239}Pu) in order to provide a calibration for the deposited energies.

The energy released into the detector, E_{dep} depends on the recoiling angle between the neutron and the ^{12}C with the scattering law $E_{dep}=0.284*E_n\cos^2\theta_R$. The finite energy resolution of the system broadens the shape of the shoulder located at the maximum energy transfer to ^{12}C at $0.284*E_n$. The better is the pulse height energy resolution the narrower is the edge. The capability of the SDD to provide spectroscopic information on the incoming neutron spectrum is very closely related to the broadening of this shoulder and to its stability versus time and varying neutron fluxes. The depth of the valley before the shoulder depends on the differential elastic scattering cross section and on the number of the neutrons scattered in the environment. The contribution related to the gamma background it is estimated to give rise to events up to 0.5 MeV. At E_{dep} lower than 0.2 MeV, the electronic noise prevents the measurement; therefore the pulse height spectra are shown only in the region [0.2; 1.2] MeV. The experimental results here described are compared in the next paragraph with Monte Carlo simulations in order to provide a full description of the detector response function.

III. MEASUREMENTS AND COMPARISON WITH SIMULATIONS

The experimental spectrum recorded for 2.5 MeV neutrons at the Pecking University (see Figure 3) is used as example to describe the data analysis procedure. The pulse height spectrum is compared and fitted with simulations made of three components: i) direct neutrons; ii) scattered neutrons; iii) gamma rays.

The energy released in the diamond bulk by the elastic scattering on ^{12}C was simulated with MCNPX[22] considering monoenergetic neutrons in the energy range from 1 to 7 MeV, every 10 keV. The pulse height spectra obtained with these simulations are then convolved with a Gaussian function in order to take into account the finite energy resolution of the system, i.e detector and electronic chain. The resulting response function, convolved with the incoming neutron beam, represents the direct neutron component (see red line of Figure 3). It must be pointed out that also the incoming neutron beam was simulated with a Monte Carlo code; the latter takes into account the p(T,^{3}He)n and p(^{7}Li,^{7}Be)n reaction cross section, the proton energy loss in the targets and the geometrical parameters of the experimental set-up.

Giving the absence of a well characterized neutron background, this was considered as a step function in the neutron energy domain: is taken equal to 1 in [0, $E_{n,max}$] MeV, where $E_{n,max}$ is the nominal incoming neutron energy, and 0 otherwise. This component, convoluted with the response function gives the SDD response to scattered neutrons (green line of Figure 3).

The gamma rays contribution (blue line of Figure 3) was simulated with MCNP6: photons are produced by proton interaction on the LiF and T-Ti targets and the pulse height spectrum in the diamond was obtained through a F8 pulse height tally.

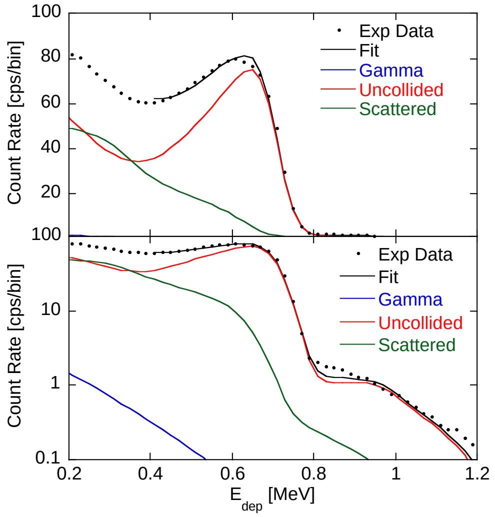

Figure 3: Experimental spectra measured with the SDD under the 2.5 MeV neutron field at the Pecking University, in lin-lin (top) and in lin-log (bottom) scale. The fit is shown in black. The gamma ray, the uncollided neutron and the scattered components are shown in blue, red and green, respectively.

As can be seen from Figure 3, the agreement between experimental data and simulation is quite good in the whole energy range. In particular it must be pointed out that the uncollided neutron component, the most important one, is the main component which contributes to the shoulder. This is a crucial point for the development of a spectrometer based on SDDs: a variation on the shoulder shape depends only on the direct neutron spectrum, and does not depend on the neutron transport between the source and the detector. In fact, as can be seen, the scattered neutron component contributes only in the valley before the shoulder. The gamma background, which can contribute up to E_{dep}=0.5 MeV, does not contribute significantly to the pulse height spectrum. The logarithmic spectrum in the bottom panel of Figure 3 features a characteristic tail for E_{dep}> 0.8 MeV. This tail, at the level of two order of magnitude lower with respect to shoulder level, is well described by the simulation and is due to multiple scattering in the diamond detector bulk. To a first approximation, we can say that the instrument sensitivity for diagnosing energetic ion population in the fusion plasma, causing emission of high energy neutrons is at a level of about 10^{-2} with respect to the main bulk emission.

By convolving the diamond detector response function with a Gaussian of FWHM (W expressed in keV unit), used in the analysis method described above, an estimation of the detector pulse height resolution is obtained.

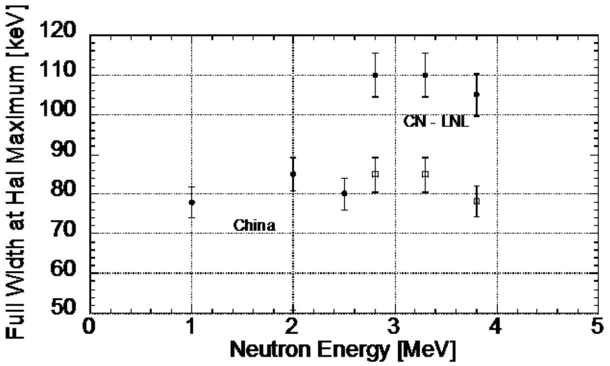

Figure 4: FWHM of the Gaussian used to convolve the simulated response function as a function of the neutron energy.

The energy resolution W found (see circle dots in Figure 4) is about 80 keV for 2.5 MeV neutrons. We observe that, for the measurement at the Pecking University, the energy resolution is constant with energy, within the available statistics. This seems to suggest that the main contribution comes from the electronic noise of the preamplifier. Concerning the measurements at the INFN-LNL, W is still constant with neutron energies but higher that in Pecking University, namely, about 110 keV. This discrepancy is likely due to uncertainties on the knowledge of the LiF target. For the estimation of the direct neutron beam an energy loss in the 700ug/cm^2 LiF target is assumed. If a narrow carbon substrate of 2 um is added before the LiF target, incoming protons would loose some energy before reaching the LiF target and the extrapolated W value would decrease to 80 keV (squared dots in Figure 4).

IV. CONCLUSIONS

A key point for the development of a neutron spectrometer based on SDDs is the knowledge of the detector response function to quasi-monoenergetic neutrons. The use of dedicated fast and low noise electronic chain has allowed to measure the diamond response function for monoenergetic neutrons in the energy range 1-5 MeV with simultaneously good pulse height energy resolution (equivalent to 80 keV at 2.5 MeV) and high count rate capability (>1 MHz). The measurements showed a very reproducible narrow shoulder, related to the scattering recoil on ^{12}C, whose position depends on the neutron energy and does not suffer gain drift due fast count rate changes or temperatures, as it is the case with liquid scintillators [23][24]. Although high resolution neutron spectroscopy at these energies is prevented by the absence of a well separated peak directly associate to the neutron interaction, as occurs in SDDs measurement for 14 MeV neutrons in DT plasmas [LG][9], a moderate resolution spectroscopy can still be achieved. By knowing the detector response function, with convolution or deconvolution methods, the pulse height spectra can be analyzed and the incoming neutron spectrum can be inferred. We observe that, in view of application to spectroscopy of D fusion plasmas, the achieved pulse height energy resolution of 80 keV for neutron energies in the range 1-4 MeV, is comparable with the contribution given by the incoming Doppler broadened 2.5 MeV neutron spectrum art T=10 keV, namely 74 keV thermal plasma. In presence of additional heating such as Neutral Beams or Radio Frequency larger contributions from the plasma are expected.

The positive SDDs features such as gain stability, compact size and good pulse height energy resolution make them attractive as compact neutron spectrometers of high flux D plasmas, such as for instance those needed for the ITER neutron camera [25][26].

ACKNOWLEDGMENT

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] M. Pillon, M. Angelone, and A. V. Krasilnikov, “14 MeV neutron spectra measurements with 4% energy resolution using a type IIa diamond detector,” Nucl. Instrum. Methods Phys. Res. B 101(4), 473–483 (1995)

[2] M. Angelone, M. Pillon, L. Bertalot, F. Orsitto, M. Marinelli, E. Milani, G. Pucella et al., “Time dependent 14MeV neutrons measurement using a polycrystalline chemical vapor deposited diamond detector at the JET tokamak,” Rev. Sci. Instrum. 76(1), 013506 (2005).

[3] M. Angelone, D. Lattanzi, M. Pillon, et al., “Development of single crystal diamond neutron detectors and test at JET tokamak,” Nucl. Instrum. Methods Phys. Res. A 595(3), 616–622 (2008).

[4] M. Rebai, C. Andreani, A. Fazzi, et al., “Fission diamond detector tests at the ISIS spallation neutron source,” Nucl. Phys. B, Proc. Suppl. 215(1), 313–315 (2011).

[5] M. Rebai, L. Giacomelli, C. Andreani, et al., “Diamond detectors for fast neutron measurements at pulsed spallation sources,” J. Instrum. 7(05), C05015 (2012).

[6] M. Rebai et al. Diamond & Related Materials 61 (2016) 1–6

[7] M. Rebai et al., Journal of Instrum 8 P10007 (2013)

[8] C. Cazzaniga et. Al. Rev. of Sci. Instrum. 85, 043506 (2014)

[9] Giacomelli et al., this conference.

[10] M. Nocente et al. Rev. Sci. Instrum. 86, 103501 (2015);

[11] *C. Cazzaniga et. al*, Rev. of Sci. Instrum. 85, 11E101 (2014)

[12] J.Y. Wang, L.H. Gong, X.J. Yang, J.H. Gong, X.C. Lu, http://en.cnki.com.cn/Article_en/CJFDTOTAL-YZJS2008S1049.htm.

[13] X. Yuan, X. Zhang, X. Xie, G. Gorini, Z. Chen, X. Peng, J. Chen, G. Zhang, T. Fan, G. Zhong, JINST 8 (2013) P07016.

[14] http://www.lnl.infn.it

[15] D. M. Trucchi et al., IEEE Electron Device Lett. 33, 615 - 617 (2012).

[16] M. Girolami et al., IEEE Electron Device Lett. 33, 224 - 226 (2012).

[17] D. M. Trucchi et al., Diamond Relat. Mater. 14, 575 - 579 (2005).

[18] Element Six Ltd, http://www.e6.com

[19] M. Girolami et al., \emph{Appl. Phys. Lett}. 103, 083502 (2013).

[20] CIVIDEC, see http://www.cividec.at.

[21] CAEN, see http://www.caen.it.

[22] http://mcnp-green.lanl.gov/

[23] Francesco Belli, Sean Conroy, Basilio Esposito, Luca Giacomelli, et al. "Conceptual Design, Development and Preliminary Tests of a Compact NeutronSpectrometer for the JET Experiment", IEEE Trans. on Nucl. Scien, VOL. 59, NO. 5, (2012)

[24] L. Giacomelli, A. Zimbal, K. Tittelmeier, et al, "The compact neutron spectrometer at ASDEX Upgrade", Rev. Sci. Instrum. 82 123504 (2011)

[25] L. Giacomelli, S. Conroy, F. Belli, et. al. "High Rate Measurements of the Neutron Camera and Broadband Neutron Spectrometer at JET" Physics Procedia 62 (2015) 124-128

[26] J. Bielecki, L. Giacomelli, V. Kiptily, et al. "Phillips-Tikhonov regularization with a priori information for neutron emission tomographic reconstruction on Joint European Torus " Rev. Sci. Instrum. 86 093505 (2015)