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Characterization of a Diamond Detector to be used as Neutron Yield Monitor during the in-vessel Calibration of JET Neutron Detectors in preparation of the DT Experiment.

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

A new Deuterium-Tritium (DT) campaign is planned at JET. The JET neutron emission monitoring system, consisting of some fission chambers and of an activation system, was recalibrated in 2013 for the 2.5 MeV neutrons, using a ^{252}Cf neutron source moved remotely to about 200 positions inside the JET vacuum vessel. However, it is not possible to proceed with a direct extrapolation to the 14 MeV neutron energy because this would lead to larger uncertainties. Therefore, and in order to obtain a full scientific return for the investment in the DT campaign, an accurate calibration for the 14 MeV neutron energy is necessary. A 14 MeV Neutron Generator with suitable intensity (≈10^8n/s) will be used at JET. The Neutron Generator intensity and energy spectrum of neutron emission will have to be calibrated and accurately pre-characterized versus the emission angles. Due to intensity change during the Neutron Generator lifetime, it would be also necessary to monitor continuously the neutron emission intensity during the in-vessel calibration using a compact detector attached to it. A high quality diamond detector has been chosen as one of the monitor. This detector, has been fully characterized at the 14 MeV Frascati Neutron Generator facility. The characterization procedure and the resulting 14 MeV neutron response of the detector are described in this paper together with the obtained uncertainties.

Keywords: Diamond detectors, Neutron detector calibration, Neutron spectroscopy, Fusion neutron diagnostics.

1. Introduction

In order to fully exploit the nominal available neutron budget and to obtain a full scientific return for the investment into the DT campaign, an accurate calibration of JET neutron detectors (^{235}U fission chambers and the in-vessel activation system) at 14 MeV neutron energy must be performed using a DT Neutron Generator (NG) deployed inside the JET vacuum vessel by remote handling. The calibration, that will take advantage of the experience gained with the recent calibration at 2.5 MeV neutron energy, will also benchmark the calibration procedure envisaged in ITER [1].

An ad hoc project has been lunched for this purpose which started as part of the JET component of the EFDA 2013 Work Programme and is continuing in the EUROfusion activities in 2014-15 and beyond until the execution of the in-vessel calibration of JET neutron detectors at 14 MeV neutron energy (scheduled in 2016). Due to the large temporal span of the planned activities, it has been considered opportune to split the project in two phases. The first one is devoted to the procurement and full characterization of the NG and its monitoring detectors. The second phase will be devoted to the in-vessel calibration and to the data analyses. The target accuracy for the JET neutron detector calibration is ±10%, which requires an even better accuracy for the NG calibration.

A Single Crystal Diamond detector (SCD) has been chosen by ENEA as one of the small detector to monitor the NG yield. The detector and the electronics needed for acquisition of the time dependent neutron response have been bought from CAEN Company [1]. CAEN has requested the construction of the detector to Istituto di Struttura della Materia (ISM), Consiglio Nazionale delle Ricerche (CNR), Rome, Italy while the electronics are standard CAEN catalogue units. These electronics are a one channel charge sensitive preamplifier, up to 200 pF input capacitance, 45 mV/MeV (Si) sensitivity and the DT5780, a Dual Digital Multi Channel Analyzer (MCA) based on a 14-bits 100 MS/s flash ADC. DT5780 accepts directly pulses from the charge sensitive preamplifier performing a digital trapezoidal shaping on exponential decaying signals. Complete control of all the shaping parameters like trapezoid rise time, flat top, etc is possible. Two HV channels able to supply a bias voltage up to ±0.5 kV, 300 uA and two connectors to power preamplifier are part of the DT5780 bought by ENEA.

ISM-CNR has produced the detector using an “electronic grade” (with [N] <5 ppb and [B] <1 ppb) CVD single crystal diamond plate (4.5x4.5mm^2, with thickness d=500 m), provided by Element Six Ltd [2]. ISM-CNR deposited square 200 nm thick multilayer gold finished contacts, 4.2x4.2mm^2, on both plate faces and then mounted the plate in an anodized aluminium casing using an alumina plate holder. A standard SMA connector is then used to pick-up the signal output, see Fig. 1.

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Fig. 1. Diamond detector sketch

As said before this detector and the electronics will be used to monitor the neutron yield of the NG that will be moved inside JET vacuum vessel using an articulated boom named MASCOT in order to perform the calibration of JET neutron detectors. A sketch of the MASCOT holding the NG is shown in Fig. 2. For this purpose, the NG will be absolutely calibrated in a neutron laboratory. The diamond detector will be located close to the NG in a well-defined and fixed position both during the NG calibration and during the in-vessel calibration of JET neutron detectors [1].

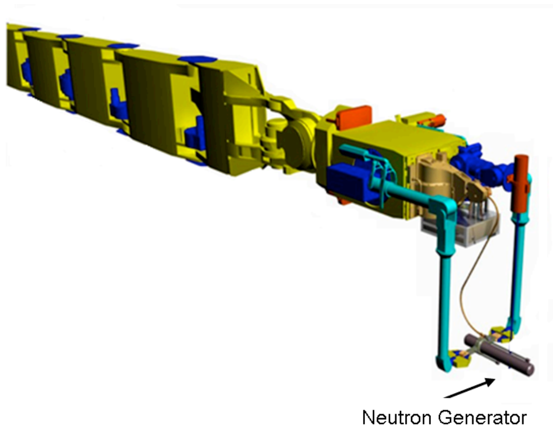

Fig. 2 Sketch of the MASCOT carrying the neutron generator. The MASCOT will go inside JET vacuum vessel.

The MASCOT remote handling has a limit about the weight it can transport hence a preliminary requirement for the yield monitor is that the weight of the detector and the electronics (here after named "monitor") must be below one kg. This was one of the reasons it has been chosen a small SCD and a compact MCA digitizer as monitor.

2. Studies of the monitor response.

2.1 Response of the monitor to alpha particles.

A preliminary characterization of the monitor was performed using a standard triple nuclide alpha source. The diamond detector was enclosed in a vacuum chamber and the electronics was connected using the cables with the length that will be necessary during the operation with the MASCOT. Tests were performed at positive and negative bias polarity applied at the detector in the range 200-400V. It was found that the peaks positions, the energy resolution and the time stability were similar for the range ±300-400V with a little improvement using a negative bias and the alphas entering the grounded diamond plate face. The typical response to alpha particles for -300V bias is shown in Fig. 3. The total measuring time was one hour long, no "polarization effects" were observed.

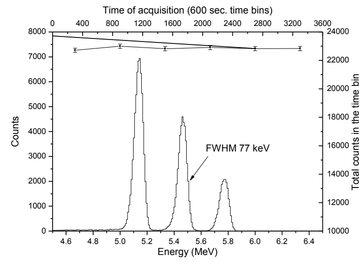

Fig. 3. Triple nuclide alpha source pulse height spectrum and time dependent stability of the counts (err bars ±1σ).

2.2 Response of the monitor to 14 MeV D-T fusion neutrons.

The monitor response to D-T fusion neutrons was measured using the Frascati Neutron Generator (FNG) [3]. FNG was employed with an acceleration voltage of 260 kV and a ~14 MeV neutron output of about $7x10^9$ n/s. With this acceleration voltage the energy of the produced neutrons span the range 13.1-15.2 MeV for angles 180°-0° with respect to the deuteron beam direction [4]. In order to study the response of the monitor to different energies the diamond detector was positioned at 22 different angles in front of FNG neutron target using a step motor which can perform a 360° rotation in $2x10^4$ steps. The angles investigated spam from -90° to 120°, in 10° angle step. Other angles were not accessible due to the presence of obstacles. The nominal distance of the centre of the diamond plate from the neutron production plane of FNG target was 31.5 cm. An uncertainty on this distance however exists and will be discussed later. The charge preamplifier and the MCA were located about 2 m far from the neutron target. In Fig. 4 a photo of the diamond detector assembly is shown. The SCD was biased at -300V in all the runs, the bias voltage was never switched off during the whole experiment which was lasting about three hours. Again no "polarization effects" were observed.

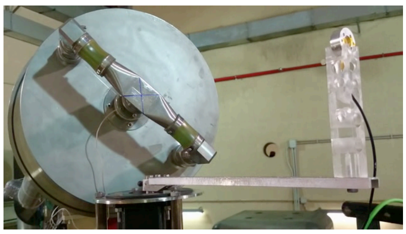

Fig. 4. The diamond detector attached to the arm of the step motor in front of FNG neutron target.

For each angle, an irradiation for a time duration of 600 seconds was carried out. In Fig. 5 the recorded time trace of the counts in the SCD at the various angles is compared with the time trace of FNG yield monitor, the associated alpha particle detector [3]. The different dependence of the profile of the counts in the SCD respect to the yield monitor is due to the presence of the pipes which bring the cooling water to the target (see Fig. 4). In order to obtain the absolute efficiency of the SCD, the predicted flux at the SCD positions was calculated using a modified version of MCNP-5 code which includes a source subroutine containing a detailed description the energy-angle distribution of the neutrons produced for the acceleration energy and target data used at FNG [5]. A plot of the MCNP-5 target geometry model is shown in Fig. 6.

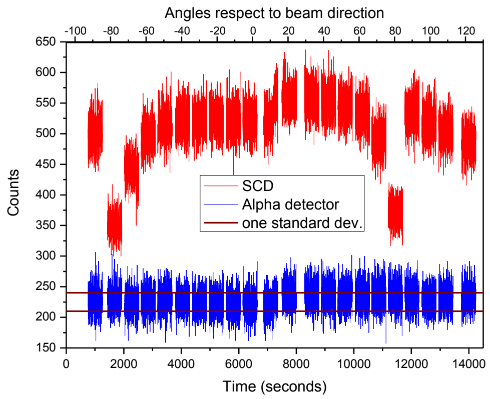

Fig. 5. Comparison of the time traces of the 22 irradiations; SCD and FNG yield monitor.

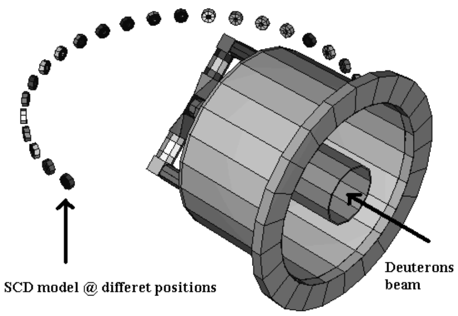

Fig. 6. MCNP-5 model used to describe the SCD positions and the FNG target holder

The MCNP-5 calculated neutron spectra at the various angular positions, normalized to the produced neutron yields, are gathered in Fig. 7 while the corresponding experimental measured Pulse Height Spectra (PHS) in the SCD are shown in Fig. 8. The calculated neutron spectra have an energy distribution strongly dependent from the angle where the detector is located, this is due to the kinematics of the beam-target interaction for the D-T fusion reaction [3].

The PHSs are plotted as a function of the deposited energy in the SCD. The deposited energy is the sum of the energy of the neutron reaction products, e.g. for example the ^{4}He+^{9}Be from the ^{12}C(n,α)^{9}Be reactions (Q=-5.7 MeV). This reaction is responsible of the most energetic peaks visible in Fig. 8.

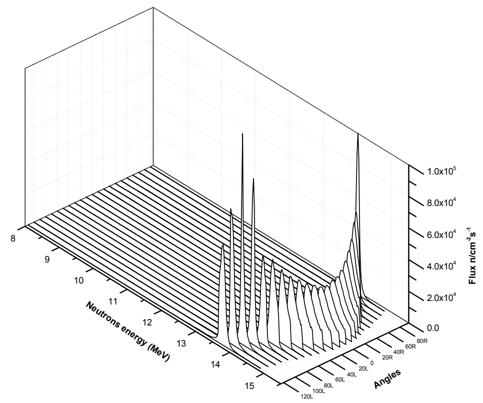

Fig. 7. Calculated neutron spectra, the values have been normalized to the neutron yields

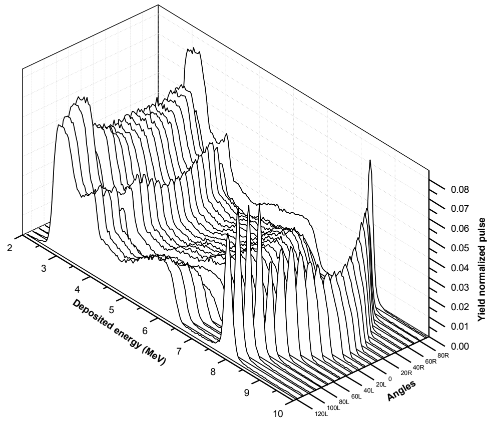

Fig. 8. Measured PHS in the diamond detector

The total counts in the ^{12}C(n,α)^{9}Be peaks have been used to calculate the detector efficiency and compare it with the calculated one. To make this comparison, knowledge of the detector active volume is necessary together with the number of ^{12}C atoms in a cubic centimetre and the value of the ^{12}C(n,α)^{9}Be reaction cross section. These values are respectively, 4.2x4.2x0.5mm^{3} = 8.82x10^{-3} cm^{3} and 1.765x10^{23} atoms/cm^{3}, while an average value of the cross section for the energy range 13.1-15.2 MeV was taken from EAF-2007 data base [6]. The value used is 73.27 mb. The results of the experiment-calculation comparison are shown in Fig. 9. The results have been normalized to a unitary fluence.

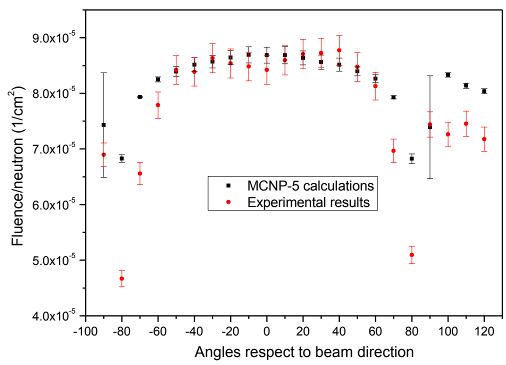

Fig. 9. Comparison between calculations and measures.

The Monte Carlo calculation points have been determined assuming an error in the distance of the SCD from the neutron target of 0.5 cm, calculating the average from the two MCNP-5 runs and half of the difference as uncertainty. This was necessary because already the calculation for the reference distance (31.5 cm) had indicated some discrepancies that increase with the angle. The statistical errors of the Monte Carlo calculation are negligible. The experimental uncertainties include the counts statistical uncertainty and the uncertainty in the absolute FNG neutron yield measurement (±3%). The experimental points for positions at angles larger than about 50° (in absolute value) are not well reproduced. This fact could be due a higher uncertainty in the SCD distance, or in its position respect to the centre of the target axis, which should correspond to the centre of the neutron emission, or also could be due to the dimension of the neutron source spot, assumed a disc of 1 cm diameter in the present calculation. However we presume that the higher contribution to the discrepancies is due to the difference between the MCNP-5 geometric model and the real target support. Indeed the FNG target support was designed very light for the neutrons going in the forward direction, having only a total of 3 mm thickness of materials (1+1+1 mm of Cu+Water+SS304). At lateral positions, on both sides of the target, there is a conical tapered tube for the cooling water of the target plus other junction parts. These pieces are difficult to model and are on the line of sights for the angles > 50° - 60°, see Fig 10. Further studies are planned to improve the MCNP-5 target model, pushed by the results of this paper.

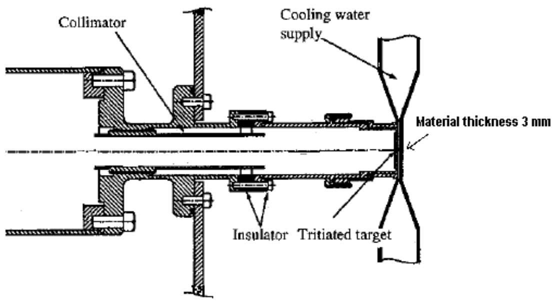

Fig. 10. Mechanical drawing of the target support.

The measured SCD neutron detection efficiency is gathered in table 1.

Table 1. Measured SCD efficiency

Angle Deg	En MeV	Peak efficiency C/n	Total efficiency C/n
50	14.55	2.00E-5 ±6E-7	1.60E-4 ±5E-6
40	14.64	2.00E-5 ±9E-7	1.59E-4 ±5E-6
30	14.71	2.02E-5 ±8E-7	1.60E-4 ±5E-6
20	14.76	1.99E-5 ±7E-7	1.59E-4 ±5E-6
10	14.80	1.96E-5 ±6E-7	1.60E-4 ±5E-6
0	14.81	1.93E-5 ±6E-7	1.59E-4 ±5E-6

The data reported are only for the angle-energy positions in the range -50° + 50° and the results for symmetric angles with respect to the beam axis have been averaged. The indicated peak efficiency refers to the counts due to the $^{12}C(n,\alpha)^{9}Be$ reaction. The total efficiency refers to all counts above the threshold of ≈ 2.5 MeV of deposited energy (see Fig. 8). This energy corresponds to about 9 MeV incident neutron energy, deposited mainly through the reaction $^{12}C(n,n')^{12}C$ [7]. The total uncertainties are ≤4.5%.

Concerning the energy resolution of the SCD and its fast neutron spectroscopy properties an approach similar to the one described in ref. 7 was adopted. The MCNP-5 calculated neutron spectra were folded assuming a gaussian response of the SCD. The parameters of the gaussian function were determined with a least squares adjustment between the gaussian folded neutron spectra and the PHS in the region of the $^{12}C(n,a)^{9}Be$ peak. The assumed uncertainty of 0.5 cm in the SCD distance from the neutron target produces effects also in the width of the neutron spectra and hence in the SCD energy resolution determined with the least squares adjustment procedure. Thus the SCD energy resolution was obtained only for the positions in the angles interval -50°, + 50°, averaging the results for symmetric angles and assuming as uncertainties half of the spread between the results for the reference detector distance (31.5 cm) and the shifted position (31 cm). Examples of the folding results are given in Figs. 11-12 for the case with SCD at 0° angle.

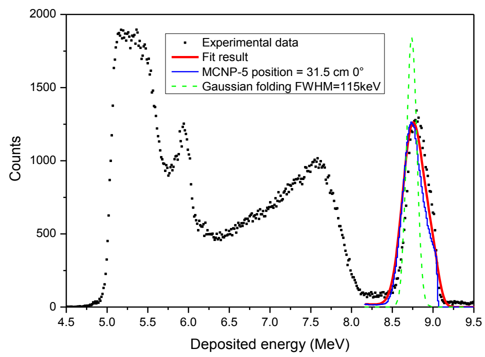

Fig. 11. Plots comparing the MCNP-5 calculated spectrum, the experimental PHS and the fitting and folding curves for the 0° - 31.5 cm position.

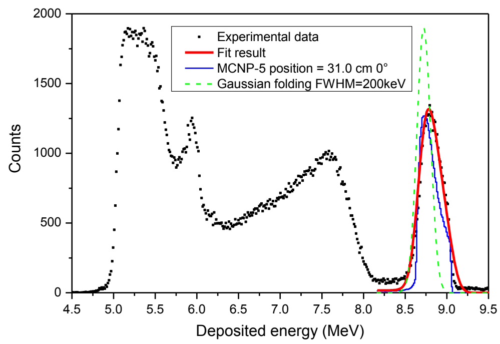

Fig. 12. Plots comparing the MCNP-5 calculated spectrum, the experimental PHS and the fitting and folding curves for the 0° - 31.0 cm position.

All the results are shown in Fig. 13 together with the measured energy resolutions for the triple nuclide alpha source and the extrapolation based on the alpha particle resolutions.

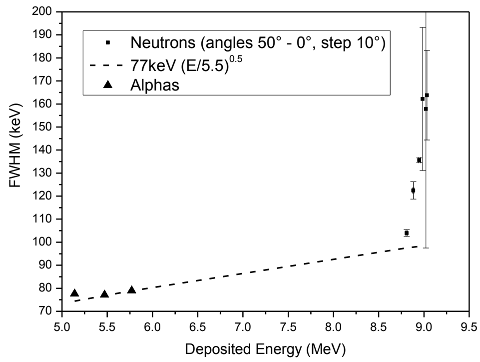

Fig. 13. Measured detector resolution

The FWHM of the $^{12}C(n,\alpha)^{9}Be$ is less then 2% for 14 MeV neutrons.

3. Conclusions

A Single Crystal Diamond detector and a compact MCA digitized, provided with a single channel charge preamplifier, have been chosen to be used as the yield monitor of the portable 14 MeV neutron generator which will be employed for the calibration of JET neutron detectors used during the D-T campaign. The response of this monitor has been characterized in term of efficiency, time stability and resolution using FNG. The results and the performances of the monitor meet the requirements of the JET neutron calibration project.

Acknowledgments

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