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Evaluation of the energy calibration of diamond detectors for fast neutrons applications

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Abstract—**The radiation hardness, the chemical resistance, and the capabilities to operate at high temperature conditions make diamond detectors a good option for carrying out fast neutron measurements on fusion plasma experiments or facilities using accelerator-driven neutron sources. A correct energy calibration of pulse-height spectra acquired through diamond detectors allows to perform fast neutron spectrometry. As a general rule, energy calibration of diamond detectors is performed using an alpha source, e.g. ^{239}Pu, ^{241}Am, ^{244}Cm, whose characteristic emission energies are in the range from 5 to 6 MeV. Calibration at higher energies, such as those related to charged particles (about 8.4 MeV) produced by the ^{12}C(n,alpha)^{9}Be induced by fast neutrons coming from D-T fusion reaction, is traditionally extrapolated with the hypothesis of linearity for the energy calibration curve. In this work an evaluation of the diamond detector energy calibration based on alpha source emissions is performed at higher energies by means of a compact D-T neutron generator, able to produce neutrons within a broad energy range, by changing the accelerator voltage and the neutron emission angle. A relative deviation less than 2% between experimental and theoretical energies was observed, showing that the energy calibration through alpha sources could be still valid for fast neutrons coming from D-T fusion reactions.**

Keywords — **diamond detectors, fusion experiments, energy calibration, fast neutrons**

I. INTRODUCTION

Diamond detectors are widely used in high energy physics and nuclear fusion experiments because of their resistance to hostile radiation environments [1]. For instance, they are part of the diagnostic designed for the International Thermonuclear Experimental Reactor (ITER) [2] and they are currently used in Joint European Torus (JET) [3]. Additionally, they can be used as point-like probe for characterizing the neutron field emitted by accelerator-driven neutron sources, as compact D-T neutron generators involved in detection of hidden explosives [4] or fissile material [5] and in almost every field of industry and research [6].

In a diamond detector, neutron detection occurs by means of charged particles produced by nuclear reactions involving the carbon nuclei. In the particular case of fast neutrons with energies higher than 5.702 MeV, the pulse-height spectrum resulting from neutron-induced reactions shows a well isolated peak corresponding to the ^{12}C(n,alpha)^{9}Be reaction byproducts, and directly proportional to the incident neutron energy [7]. A correct energy calibration of pulse-height spectrum allows to perform fast neutron spectrometry. As a general rule, energy calibration of diamond detectors is performed using an alpha source, whose characteristic emission energies lie in the range from 5 to 6 MeV. Calibration at higher energies, such as those related to charged particles produced by the ^{12}C(n,alpha)^{9}Be induced by fast neutrons from D-T fusion reaction, is traditionally extrapolated with the hypothesis of linearity for the energy calibration curve obtained by considering the alpha source [3,7-9].

Usually, in radiation spectrometry (e.g., gamma or alpha spectrometry) the energy calibration is performed using sources emitting radiation with energies that cover the whole energy interval of interest, with experimental points included in such energy range. If possible, linear extrapolation should not be used to extend the energy calibration outside the range where the measured points of the calibration source actually lie.

In this paper, an experimental evaluation of the energy calibration of a diamond detector obtained by means of an alpha source to higher energies by using a D-T neutron generator is carried out, being the neutron generator able to produce neutrons within a broad energy range. This will build confidence in adopting the alpha calibration within conditions closer to real application of diamond detectors.

II. EXPERIMENTAL SETUP

A. Single crystal diamond detector

A small size diamond detector, i.e. 4.7 mm x 4.7 mm x 0.5 mm, obtained by chemical vapor deposition [10] was used as fast neutrons detector (Fig. 1).

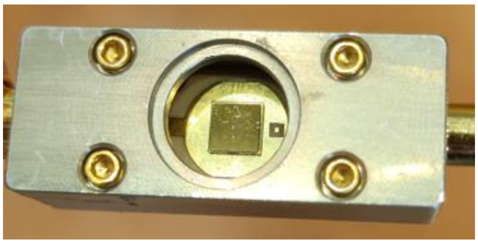

Fig. 1. Diamond detector.

The diamond detector working principle is similar to that of a solid-state ionization chamber. A charged particle with an energy greater than its band-gap produced ionization through the diamond, and consequently generates electron-hole couples. Charges are then collected by means of an electric field. Neutrons, lacking electrical charge, do not cause direct ionization within the detector and can be detected only through secondary charged particles produced by conversion reactions. Focusing on 14 MeV neutrons emitted by D-T reaction, the best candidate reaction channel for neutron spectroscopy is the (n,alpha) reaction, ^{12}C(n,alpha)^{9}Be, whose characteristic peak in the measured pulse height spectrum (PHS) corresponds to the total energy of reaction products, ^{9}Be and alpha particle, as shown in Fig. 2. The well-isolated peak is centered at the energy E_n – 5.702 MeV, where E_n is the energy of the incident neutron, and 5.702 MeV is the threshold over which the reaction between neutrons and ^{12}C can occur.

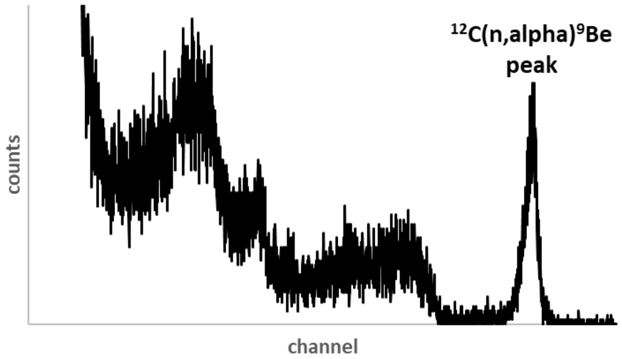

Fig. 2. Measured pulse height spectrum for 14 MeV neutrons interacting with a diamond detector.

B. Calibration sources

For the experiments two types of calibration sources were used: certified alpha sources and a compact D-T neutron generator.

To collect calibration points in an adequate energy range, two certified alpha sources were used, one containing ^{237}Np, ^{241}Am, and ^{244}Cm and the other one containing ^{239}Pu, ^{241}Am, and ^{244}Cm. Characteristic alpha energies emitted by the aforementioned radionuclides are listed in Table I.

TABLE I
CHARACTERISTIC MOST PROBABLE ENERGIES EMITTED FROM ALPHA SOURCES

Radionuclides	Energy for the most probable alpha emissions (MeV)
^{237}Np	4.788
^{239}Pu	5.157
^{241}Am	5.486
^{244}Cm	5.805

Since the experiments were performed in air, an appropriate correction was introduced for estimating the actual energy of the alpha particle on the detector, taking into account the loss of energy due to the air thickness between detector and alpha source.

A D-T compact neutron generator was used as alternative source of secondary charged particles through neutrons interactions. Inside the generator a beam of deuterons is accelerated and hits a metallic target where tritium is adsorbed on. The D-T fusion reaction ^{3}H(d,n)^{4}He produces fast neutrons emitted in the whole solid angle. The theoretical energy of the emitted neutron E_n depends on its emission direction with respect to incident deuteron direction θ as well as on the deuteron energy E_d, directly linked to the accelerator voltage, following kinematic of the reaction:

$$\sqrt{E_n(\theta, E_d)} = A + \sqrt{A^2 + B} \tag{1}$$

where

$$A = \frac{\sqrt{M_d M_n E_d}\cos\theta}{M_\alpha + M_n} \quad (2); \quad B = \frac{M_\alpha Q + E_d(M_\alpha - M_d)}{M_\alpha + M_n} \quad (3)$$

with M_d, M_α, M_n the masses of deuteron, alpha particle, and neutron, respectively. While Q is the reaction Q-value which, for the fusion nuclear reaction ^{3}H(d,n)^{4}He has a value of 17.59 MeV [11]. Since the accelerator voltage is selectable between 40 kV and 90 kV, it offers the possibility to produce neutrons within a broad energy range around 14 MeV. In Fig. 3, the neutron energy as a function of its emerging angle is shown, produced in the case of a deuteron acceleration voltage of 40 kV and 90 kV.

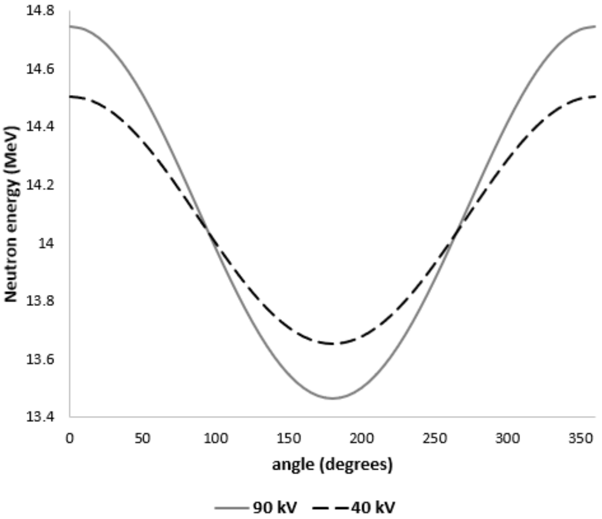

Fig. 3. Neutron energy as a function of its emerging angle from D-T neutron generator. The solid line shows the energy variation for an accelerator voltage of 90 kV, the dotted line corresponds to an accelerator voltage of 40 kV.

Using the D-T neutron generator with different accelerator voltages it is possible to produce neutrons within the range 13.466 and 14.748 MeV. Since the well-isolated peak in the diamond measured PHS is centered at E_n – 5.702 MeV, these neutrons interacting with the diamond detector could produce secondary charged particles with a total energy deposition inside the diamond crystal between 7.764 MeV and 9.046 MeV, thus over the energy range covered by the alpha sources.

C. Standard calibration procedure

The certified point alpha sources were placed one at a time on the detector and the two PHS shown in Fig. 4 were acquired and recorded.

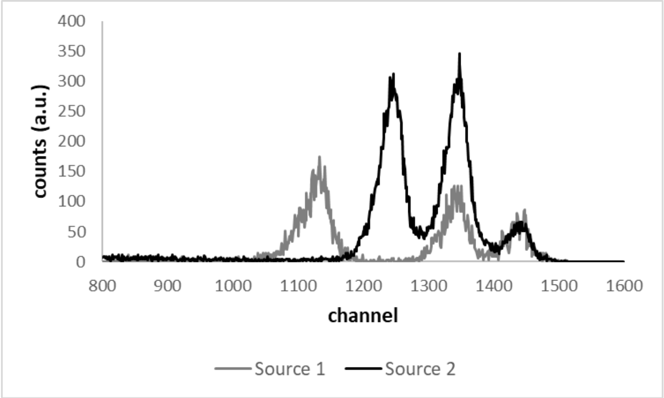

Fig. 4. Measured PHS for certified alpha sources. In grey Source 1 (^{237}Np, ^{241}Am, and ^{244}Cm), in black Source 2 (^{239}Pu, ^{241}Am, and ^{244}Cm).

A standard calibration of the PHS was performed, associating the channels of the peak centroids to the corresponding alpha energies and performing a least squares regression. The goodness of the regression was evaluated through the R-square that resulted 0.9998. Usually in radiation spectrometry (i.e., gamma or alpha spectrometry) the energy calibration is performed using sources emitting radiation with energies that cover the whole energy interval of interest, with experimental points included in such energy range.

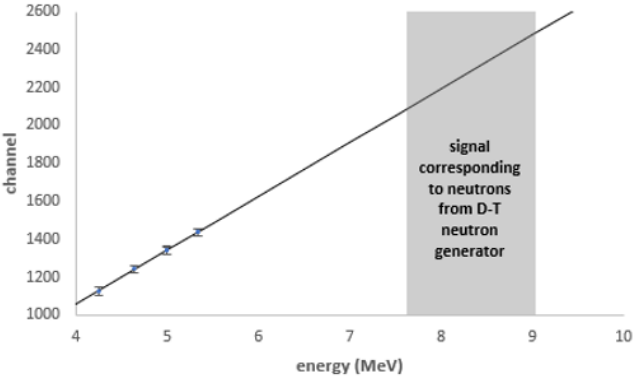

Fig. 5. Regression line corresponding to the standard calibration procedure (R-square = 0.9998). On the left the experimental points corresponding to alpha sources emissions, on the right in grey the region related to neutrons from D-T neutron generator.

In this case, the regression line is based on experimental points corresponding to energies between 4.246 MeV and 5.331 MeV, relatively far away, in terms of energy, from the region related to the signal coming from D-T neutrons, highlighted in grey in Fig. 5.

For this reason, an experimental evaluation of the standard calibration through alpha sources was performed using the compact D-T neutron generator.

D. Experimental evaluation of standard calibration for 14 MeV neutrons

To record PHS related to different neutron energies the diamond detector was mounted on a metal arm solidly connected to the generator and able to rotate around the center of the target (Fig. 6). Such a configuration makes it possible to acquire the neutron energy spectra at different angular positions with respect to the deuteron ions direction.

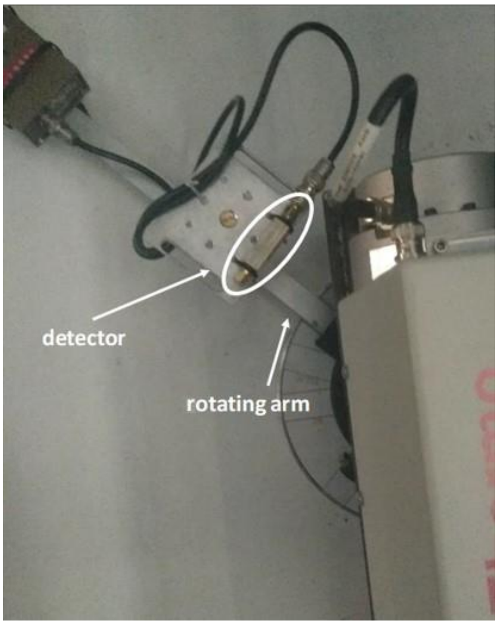

Fig. 6. Experimental setup. Diamond detector mounted on a metal rotating arm solidly connected to the neutron generator.

To maximize the flux and consequently minimize the measurement time, the smallest allowed detector-to-target distance was chosen. Given the overall dimensions of the neutron generator, such a distance is 17 cm. A semicircle with a radius of 17 cm has been sampled in 8 positions, illustrated in Fig. 7.

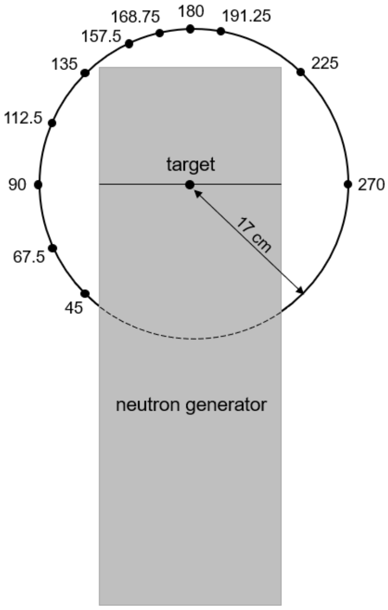

Fig. 7. Diamond detector experimental positions around the compact D-T neutron generator.

Additional measurements were carried out to verify the irradiation symmetry. Measurements with θ < 45° was not investigated because of the overall dimensions of the device, preventing the detector to be placed at the minimum selected distance for those angles. Three sets of measurements were performed corresponding to three different accelerating voltages, 50 kV, 80 kV, and 90 kV. The 80 kV measurements set investigated all the 11 positions, the other two sets focused on 6 of them (45°, 135°, 157.5°, 168.75°, 180°, and 270°).

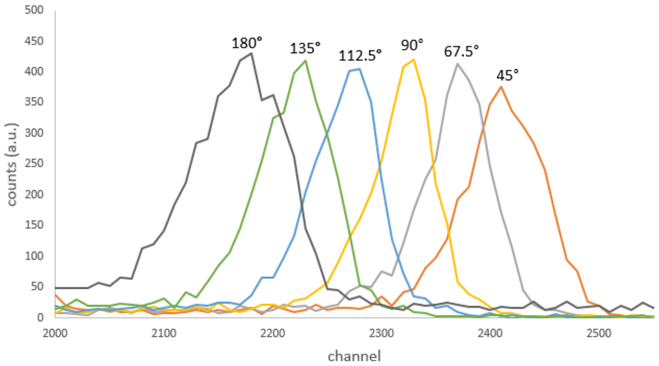

Fig. 8. $^{12}C(n,alpha)^{9}Be$ reaction peak at different detector positions for an accelerating voltage of 80kV.

Focusing on the position of $^{12}C(n,alpha)^{9}Be$ reaction peak, the expected shift in channels –corresponding to the variation in energy of neutrons emitted at different angles– was recorded, as illustrated in Fig. 8.

The peak shape depends on the incident particle beam composition within the neutron generator that in general can be a mixture of D/T ions causing the presence of DT^+, D_2^+, T_2^+ T^+, and D^+ within the beam [12]. Since in this case study the accelerated beam is made of deuterons impinging on a tritiated target, the main contribution to the peak shape is expected to be due to D_2^+ and D^+ ions. The simultaneous presence of these two types of ions could cause a double-peak structure for angles near to 0° and 180°, depending on the proportion between the two types of ions. Since the ratio of D_2^+ and D^+ ions is an unknown parameter, a simplified approach considering the incident particle beam made by only one type of ions has been considered. In particular, the analysis has been performed for each case (i.e., only D^+ ions and only D_2^+ ions). In the case considering only D_2^+ ions, the molecular ion will produce two particles with half energy respect to the case considering only D^+ ions and the neutron theoretical energy will vary accordingly.

For each detector position and accelerating voltage, the characteristic peak was fitted with a Gaussian distribution function to determine the mean value (μ) and the related standard deviation (σ). With the hypothesis that neutrons interacting with diamond detector at 17 cm from the target position and causing a signal in the well isolated peak are uncollided neutrons, each mean value was associated with the respective theoretical energy (E_{th}), and the experimental points, whose coordinates in an Energy-channel reference system are (E_{th}, $\mu\pm\sigma$), were compared with the predicted values corresponding to points (E_{th}, $A+B\cdot E_{th}$), where A and B are the coefficients of the calibration regression line.

Fig. 9-10 show the experimental points related to neutrons produced at different accelerating voltages for an incident particle beam made respectively only by D^+ ions and D_2^+ ions.

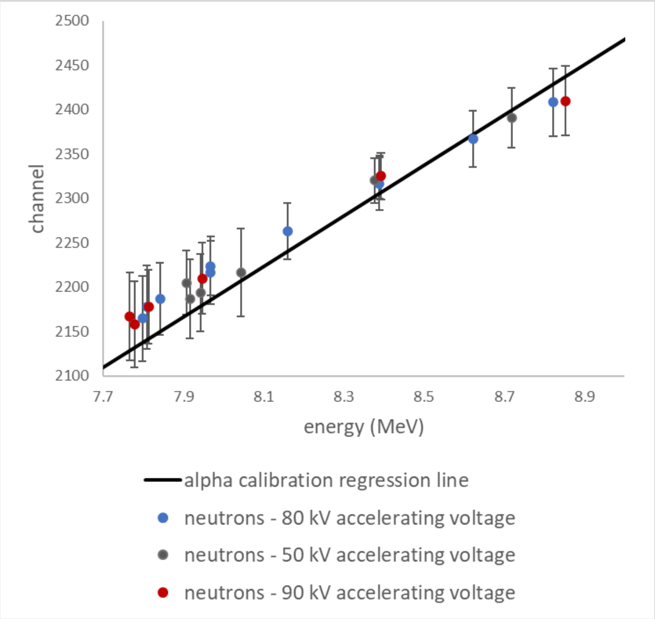

Fig. 9. Evaluation of alpha calibration regression line in the energy region 7.764 MeV - 9.046 MeV through experimental points from neutrons produced by D-T neutron generator. The incident particle beam is considered made only by D^+ ions.

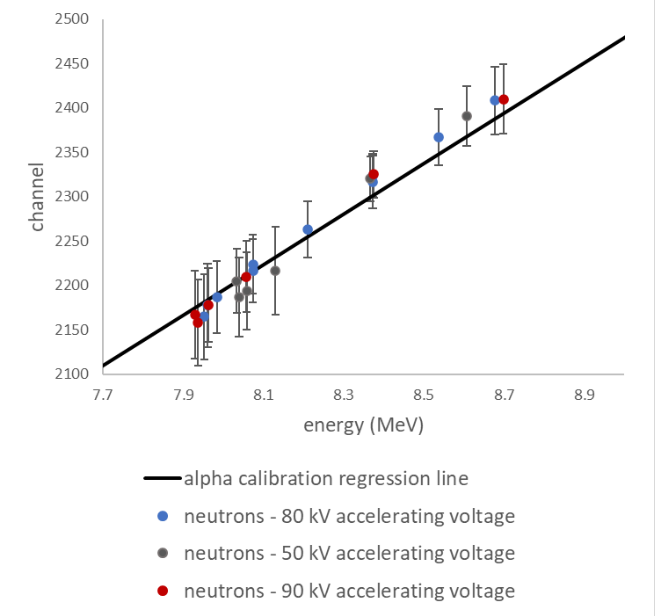

Fig. 10. Evaluation of alpha calibration regression line in the energy region 7.764 MeV - 9.046 MeV through experimental points from neutrons produced by D-T neutron generator. The incident particle beam is considered made only by D_2^+ ions.

For both hypotheses, the experimental results are consistent with predicted values within the uncertainties (assumed equal to standard deviations, σ) (Fig. 9-10), providing evidence that that diamond detector energy calibration based on alpha sources and extrapolated at higher energies is still consistent for 14 MeV neutrons produced by a D-T neutron generator.

Each centroid (μ) was associated to the corresponding energy value E_{exp} calculated via the alpha calibration, the ratio respect to theoretical value E_{th} was then evaluated.

As shown in Fig. 11-12, the relative deviation was always less than 2% for D^+ hypothesis and less than 1.05% for D_2^+ hypothesis, confirming the good agreement between experimental and theoretical values. Since the actual incident particle beam is made by a mixture of the two considered types of ions, the agreement will be still consistent.

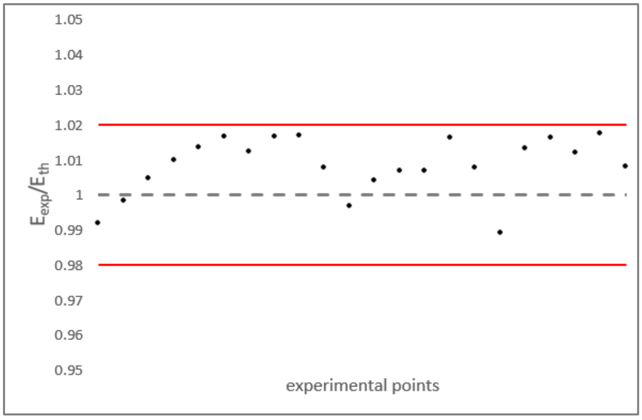

Fig. 11. E_{exp}/E_{th} ratio evaluated for the experimental points from neutrons produced by D-T neutron generator. Red lines show the 2% confidence interval. The incident particle beam is considered made only by D^+ ions.

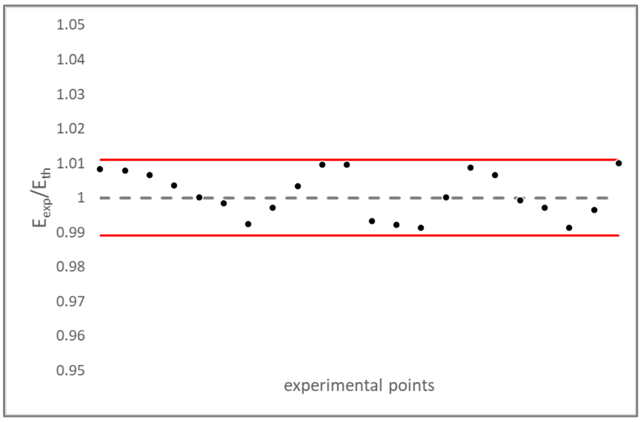

Fig. 12. E_{exp}/E_{th} ratio evaluated for the experimental points from neutrons produced by D-T neutron generator. Red lines show the 2% confidence interval. The incident particle beam is considered made only by D_2^+ ions.

III. CONCLUSIONS

In this work an evaluation of the diamond detector energy calibration based on alpha source emissions (5-6 MeV) is performed at higher energies by means of a compact D-T neutron generator. Inside the generator, a beam of deuterons is accelerated to a selectable accelerator voltage (between 40 keV and 90 kV) and impacts on a tritiated target to produce 14 MeV neutrons by means of the fusion reaction T(d,n)alpha. Because of the kinematics of the reaction, the energy of emitted neutrons is not 14 MeV in all conditions. It depends in fact on neutron emission direction with respect to incident deuterons direction as well as on the deuteron energies (i.e., directly linked to the accelerator voltage). Changing the accelerator voltage offers the possibility to produce neutrons within a broad energy range, 13.466 MeV - 14.748 MeV.

For different selected accelerator voltages, several measurements with a 4.7 mm x 4.7 mm x 0.5 mm diamond detector were performed at different angular positions around the compact D-T neutron generator. The PHS corresponding to different conditions were acquired by means of a Multi Channel Analyzer and calibrated in energy through alpha sources. At the same time, a simple theoretical model is used for calculating the energy and the relative uncertainty of emitted neutrons in each case, in order to evaluate the effectiveness of the diamond detector energy calibration extrapolation at energies higher than those used for the traditional alpha calibration process. The analysis has been performed for two different hypothetical compositions of the incident particle beam. A relative deviation less than 2% between evaluated and theoretical energies was observed recorded showing that the PHS energy calibration of a diamond detector through alpha sources and extrapolated at higher energies could be still consistent for fast neutrons coming from D-T fusion reactions.

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