RAP Conference Proceedings, vol. 8, pp. 79–83, 2023
ISSN 2737-9973 (online) | doi: 10.37392/RapProc.2023.16
RAP-PROCEEDINGS.ORG

NOVEL DIAMOND DETECTOR DEVELOPMENT FOR HARSH NEUTRON FLUX ENVIRONMENTS

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Abstract. *Diamond is considered one of the most promising materials for neutron reaction studies and neutron fluence measurements. A newly built diamond detector and associated electronics were developed by the CIVIDEC Instrumentation for in-beam neutron measurements in harsh environmental conditions (high instantaneous neutron flux, high gamma-ray background, etc). Various tests were performed to determine the detector's response to neutron environments including a measurement at NCSR "Demokritos" with monoenergetic neutron beams and a corresponding one at the newly built experimental area NEAR station at the n_TOF facility at CERN. The preliminary results of the tests for the development of this novel detection system will be presented and discussed.*

Keywords: *diamond, neutrons, NEAR station, Demokritos, GEANT4, fusion neutrons, ITER*

1. Introduction

Neutron detectors play a crucial role in numerous applications where neutron flux monitoring and neutron spectrum measurements are important. Such applications can be high energy particle physics experiments, plasma diagnostics in fusion facilities, space or medical applications, where it's important to remain operational in harsh environmental conditions. A number of neutron detection systems has been proposed, such as microfission chambers or neutron activation systems, however in the recent years semiconductor detectors exhibit unique and promising characteristics for neutron detection in various environments.

One of the main interests in nuclear physics is the production of energy via thermonuclear fusion. As a consequence, the largest experimental fusion reactor ITER (International Thermonuclear Experimental Reactor) is being built during the last years in the south of France. It will be the largest fusion machine, with a major radius of 6.2 m and a minor radius of 2.0 m, operating in a magnetic field of 5.3 T, a plasma current of 15 MA and the ultimate goal is the production of 500-700 MW fusion power through D-T fusion [1].

For the upcoming years, during the test period of ITER, experiments will be conducted with D-D plasma which leads to the production of neutrons. An important part in the feasibility study of such a reactor requires to detect those neutrons. As mentioned above, one of the promising candidates are semiconductor neutron detectors. With the proper choice of material, they can display increased efficiency and irradiation resistance.

Diamond is one of the most popular materials for constructing resilient semiconductor detectors with sufficient energy resolution, able to perform in harsh environmental conditions [2]. A new diamond system along with its electronics was developed by CIVIDEC Instrumentation [3] and was tested throughout dedicated experiments. The detector's response was first measured with a monoenergetic neutron beam at NCSR "Demokritos", as well as, with a white neutron beam at the NEAR station of the n_TOF facility at CERN. The preliminary results of these measurements along with the diamond detector characteristics and their functionality will be presented in the next sections.

1.1. Diamond Detector Characteristics

Due to its excellent electrical and physical properties diamond is considered one of the most promising materials for detector applications in harsh environmental conditions. Some of its main characteristics and advantages are presented below.

At room temperature diamond presents a bandgap energy $E_g=(5.470\pm0.05)$ eV, while common semiconductor detectors like Si or Ge exhibit a gap of 1.12 eV and 0.66 eV respectively. In the presence of an electric field, thermal generation of electron-hole pairs generate a current known as dark or leakage current. The leakage current of the diamond detector is much lower than the corresponding one of Si or Ge detectors, due to a higher value of Eg and the high resistivity

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(> 10^{13} Ohm cm) that diamond presents. The high electron and hole mobility and the high breakdown field (10 $MVcm^{-1}$), leads to a possibility of fast timing measurements with sub-nanosecond response time [2], [4].

The dielectric constant of diamond is ε=5.7, which reflects its low capacitance. This is advantageous for high energy resolution measurements, as the capacitance for a given detector-geometry is lower than for most other semiconductor materials, like Si having ε=11.9. In addition, from theoretical calculations, the energy to create an electron-hole pair in diamond is predicted to be ε=11.6 eV/e-h. A low relatively dielectric constant combined with a high Eg as well as a relatively small electron–hole pair generation energy, leads to a high signal to noise ratio in favor of the diamond detector.

The C atoms in diamond are strongly bound to each other, with 7.24 eV/bond respectively. The exceptional thermal conductivity of up to 20 $Wcm^{-1}K^{-1}$ and the relatively high displacement energy threshold of approximately 43 eV/atom derive from these strong bonds. The latter contributes to diamond's good radiation hardness. A high fusion temperature (4100°C) combined with the high thermal conductivity, are considered to make diamond suitable for operations with high temperatures. The low Z renders diamond scarcely sensitive to gamma radiation. This could be helpful when operating in mixed neutron- gamma fields, much like the conditions in high energy experiments or fusion reactors, in order to enhance and/or separate the neutron signals.

The newly built diamond detector system consists of a single-crystal diamond sensor fabricated via CVD (Chemical Vapour Deposition) technology, with dimensions 4 x 4 mm^2 and 50 μm in thickness. The sensor is packaged in a PCB (printed circuit board) structure consisting of FR4 (glass reinforced epoxy laminate material) metallized with Cu and Au. At 1 mm distance from the sCVD diamond a ^{6}LiF foil was placed during the measurements, with 1.9 μm thickness and 95% enriched with ^{6}Li.

1.2. Neutron Detection

Neutrons do not interact with Coulomb force since they are not electrically charged. They interact with matter via nuclear interactions and as a consequence they are highly penetrating. Their main interactions are through scattering (elastic, inelastic), capture (absorption), fission with heavy nuclei and neutron to charge particle (n,cp) interactions. The neutron scattering involves changing the energy and direction of the incident neutron but the target nucleus remains with the same number of nucleons. When neutron capture occurs, the target nucleus absorbs the incident neutron and emits the excess energy via gamma-rays. In all other reaction channels, a charged particle is in the exit channel of the nuclear interaction. Depending on the neutron energy and the target nucleus one or all the above processes can occur. Neutrons are detected by the charged particles they produce via each interaction. The current produced by these charged particles constitutes the measured current in the detector. The main neutron interactions with diamond (^{12}C), along with their Q value and their threshold are summarized in Table 1.

The neutron detection is based on the cross section of each reaction as shown in Figure 1. For neutrons with energies 1 MeV < En < 10 MeV the dominant interactions with the diamond are the elastic and inelastic scattering. Through this process a recoil nucleus is produced which ionizes the sensor. Nevertheless, only for neutrons with En > 1 MeV the energy deposited by the recoil ^{12}C nucleus is large enough to be detected. Consequently, for neutrons with En <1 MeV or less the most efficient way to detect them is though the ^{6}Li(n,t) reactions with the LiF converter.

For neutrons with En > 6 MeV the (n,cp) reactions enter in the play and the neutrons can be detected also through the secondary emitted charged particles (protons, deuterons or alpha particles).

Table 1. Main neutron interactions with diamond.

Nuclear Reaction	E_{th} [MeV]	Q [MeV]
^{12}C(n,el)^{12}C	0	0
^{12}C(n,n')^{12*}C (1st excited state)	4.8	0
^{12}C(n,n')^{12*}C (2nd excited state)	8.2	0
^{13}C(n,α)^{10}Be	4.1	-3.8
^{12}C(n,α)^{9}Be	6.2	-5.7
^{12}C(n,n')3α	7.9	-7.3
^{12}C(n,p)^{12}B	13.6	-12.6
^{12}C(n,d)^{11}B	14.9	-13.7

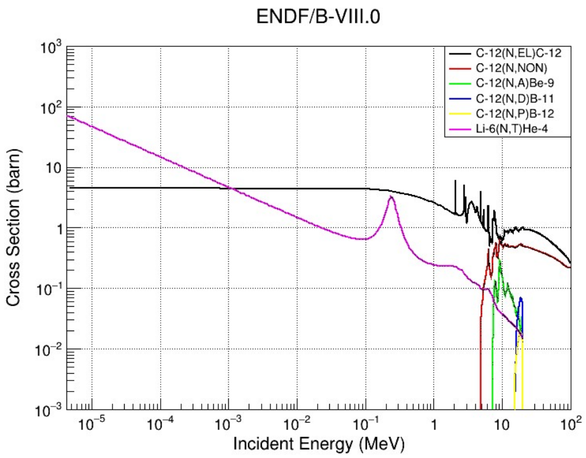

Figure 1. Cross sections of ^{6}Li(n,t) and the main neutron interactions with diamond. Data obtained from the ENDF/B-VIII.0 Database.

The diamond detector system includes the LiF foil so the detection of low energy neutrons is feasible and efficient. From the shape of the cross sections it is clear that the (n,t) reaction dominates over all the low energy neutron interactions.

For the detector characterization it is necessary to test the system response to various neutron beams and environments. The first test includes a quasi-monoenergetic neutron beam whereas the second a white neutron beam.

2. NCSR "DEMOKRITOS" TEST

The diamond detector system was first tested at the neutron production facility of the TANDEM accelerator at NCSR "Demokritos". This facility produces quasi-monoenergetic neutron beams by the interaction of light ions (protons or deuterons) with gaseous or solid targets, depending on the neutron energy of interest.

The study of 2.45 MeV neutrons was carried out due to the interest of this energy in fusion applications.

For the production of 2.45 MeV neutrons a proton beam of approximately 3.8 MeV is used. As the protons cross the experimental line, they enter the aluminum flange where the solid TiT target is placed. First, they interact with a thin Mo foil, which acts as the entrance window, then they interact with the main TiT target where the neutron beam is produced, and finally they encounter a thick Cu layer which acts as the beam stop. With this process a quasi-monoenergetic neutron beam of 2.45 MeV was produced.

The experimental line and the set-up are shown in Figure 2. The detector was placed at a distance of 12.8 mm away from the target at 0° with respect to the proton beam axis and the amplifier used was a spectroscopic 2GHz/40dB CxL0225 one, produced by CIVIDEC Instrumentation [3]. The HV supply was 3 m away from the beam line and the sCVD diamond was operated at +50 V bias voltage (<E> =1 V/μm).

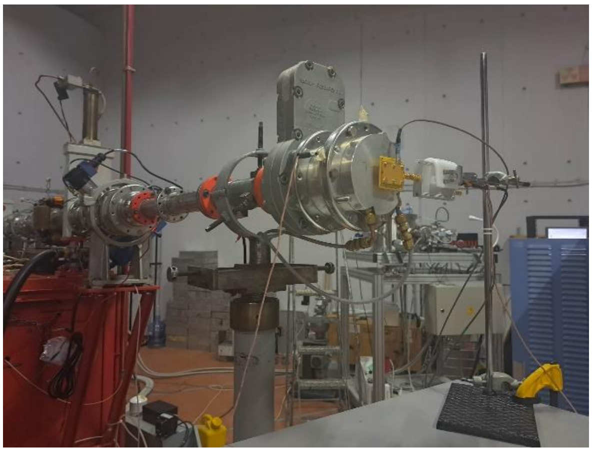

Figure 2. Experimental set-up for the diamond detector at NCSR "Demokritos".

For 2.45 MeV neutron elastic scattering is the dominant process. The diamond detector is able to record the energy deposition of the charged recoil nucleus of ^{12}C. The experimental spectrum is shown in Figure 3. We observe the characteristic cut-off for elastic scattering which according to kinematics is located around 0.7 MeV. The plateau area which extends beyond the end of elastic scattering cut-off is caused by the proton recoils from the PCB that surrounds the diamond detector.

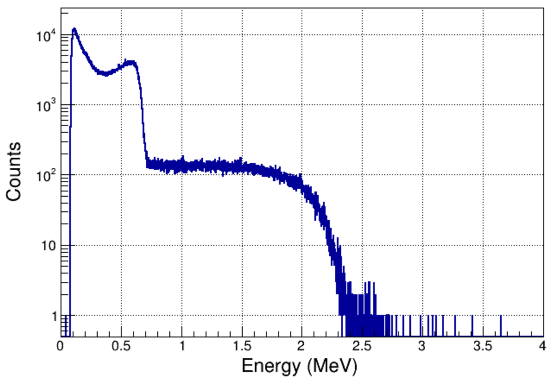

Figure 3. Deposited energy spectrum of 2.45 MeV neutrons in a 50 μm diamond detector at the NCSR "Demokritos".

2.1. Simulations

A simple simulation was performed using the Geant4 [5] Monte Carlo simulation toolkit, in order to validate the detector response for 2.45 MeV neutrons for a 50 μm diamond (C) detector. The resulting spectra are shown normalized in Figure 4. As expected, we can observe the characteristic cut-off at 0.7 MeV. The counts above the elastic region are produced via neutron interactions with the air until they reach the detector, mostly via $^{14}N(n,p)$, which results to proton energies from approximately 2.3 MeV to 3.0 MeV according to kinematics (visible in spectrum).

The simulations verify both the shape of the experimental spectrum and the cut-off [6]. However, a more realistic simulation will be performed including both the extra layers of the PCB material as well as the realistic source which produces the quasi-monoenergetic neutron beam of 2.45 MeV.

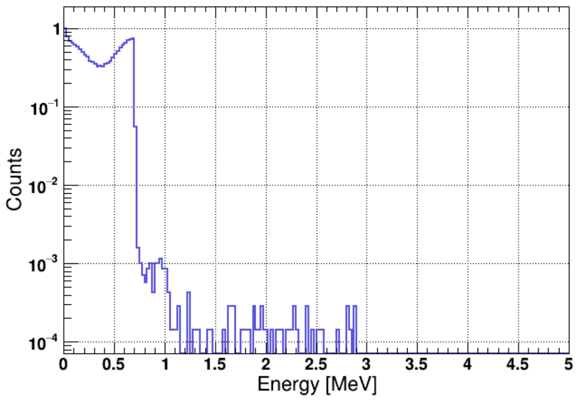

Figure 4. Simulated normalized spectrum for 2.45 MeV neutrons in a 50 μm diamond detector.

3. Test at the NEAR station

The detector response was also tested with a white neutron beam at the newly built NEAR station at the n_TOF (neutron Time Of Flight) facility at CERN. In this facility a proton beam of 20 GeV impinges on a lead spallation target and produces a pulsed neutron beam with energies that span 11 orders of magnitude [7]. The NEAR station is placed less than 3 m away from the lead target and thus, due to the harsh environmental conditions any measurement with an active detector poses a serious challenge. The simulated shape of the neutron flux is shown at reference [7] Figure 2a.

The sCVD diamond detector described in the sections above was placed centered with respect to the neutron beam axis as shown in Figure 5. For the first tests, and in order to be able to easily exchange electronics, a 70 m cable was connecting the 24 MHz C80038 amplifier to the diamond detector (the access to the NEAR station is restricted due to the intense radiation conditions). The signal was recorded with a 12-bit Oscilloscope.

This was the first time an in-beam measurement was attempted in this newly built facility using an active detector. The measurements were taken with three different proton beam intensities: 1.0×10^{12}ppp (protons per pulse), 2.0×10^{12}ppp and 8.5×10^{12}ppp and the current generated in the detector was recorded. In terms of neutron flux the 8.5×10^{12}ppp generate a maximum detector current of approximately 0.016 A per pulse (integrated at all energies as shown in Fig.6) and for the lower intensities it is scaled accordingly.

Figure 5. Experimental set-up at NEAR station.

3.1. Preliminary results

This test was able to demonstrate the feasibility of the diamond detection system in harsh environmental conditions in terms of radiation. Due to the 70 m cable an artificial reflection was observed at approximately 700 ns. To reduce this effect, a 20dB attenuator was used at the measurements with the high proton beam intensity. Figure 6 shows the comparison of the current recorded from the detector, which is the sum of all the reactions occurring in the diamond detector from the incoming neutron beam, with respect to the time of flight of the white neutron beam, for the highest proton beam intensity ($8.5x10^{12}$ppp) with the simulations.

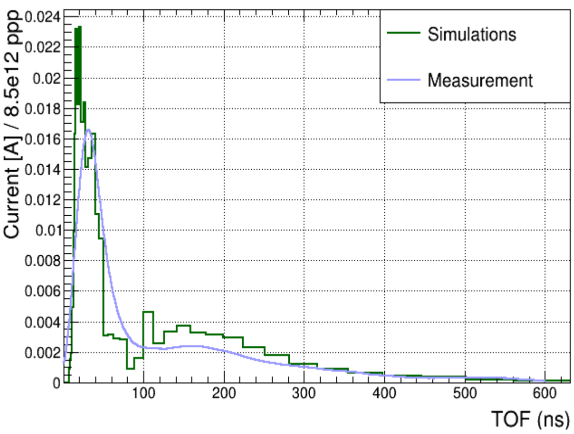

Figure 6. Preliminary results of the recorded current with respect to time-of-flight of the 50 μm diamond detector at NEAR station. The expected current based on simulations is also shown for comparison.

The simulations take into account the neutron flux provided by FLUKA simulations, which is scored in the measured position, followed by a calculation of the recorded current. More analytically, the expected current of the detector is found by multiplying the simulated neutron flux with the conversion yield, which is calculated according to the mean charge per neutron interaction, the efficiency and the cross section of the diamond detector. From the simulated TOF we extracted that $^{12}C(n,x)$ reactions are dominant for TOF < 10^3 ns, while for the Li(n,t) interactions for TOF > 10^3 ns. Consequently, in Fig.6 we observe mainly $^{12}C(n,x)$ interactions with the white neutron beam.

The simulations need refinement, such as the addition of the marble wall at the NEAR station and the detector materials, however we observe a satisfactory agreement with the recorded current of the detector in this first comparison. The same behavior is observed in all the other measurements taken for all beam intensities. Additional corrections will be implemented in further analysis, such as considering the resolution function of the facility and the electronics. Nonetheless, these first results are encouraging and demonstrate the feasibility of performing in-beam neutron flux measurements at the NEAR station.

4. Conclusion

An active diamond detector system was built and tested with two types of neutron beams. First with a 2.45 MeV quasi-monoenergetic neutron beam at NCSR "Demokritos" and secondly with a white neutron beam at the NEAR station of the n_TOF facility at CERN. The neutron beam of 2.45 MeV is of serious interest for D-D fusion experiments that are expected to run for the upcoming years at ITER. The NEAR station is considered a harsh environment in terms of radiation and it was the first time an active in-beam measurement was attempted in this facility.

The results are encouraging in both tests and show that the diamond detector behaves as expected in both cases. The detector development is ongoing with additional characterization with monoenergetic neutron beams and the electronics optimization.

Acknowledgements: *This work was supported by all the members of the NTUA nuclear physics group and our colleagues from NCSR "Demokritos" and the n_TOF collaboration in many different ways. The authors gratefully acknowledge the financial support by the PEVE 2021 project of NTUA and the ARIEL project. This work was supported by CIVIDEC Instrumentation GmbH.*

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