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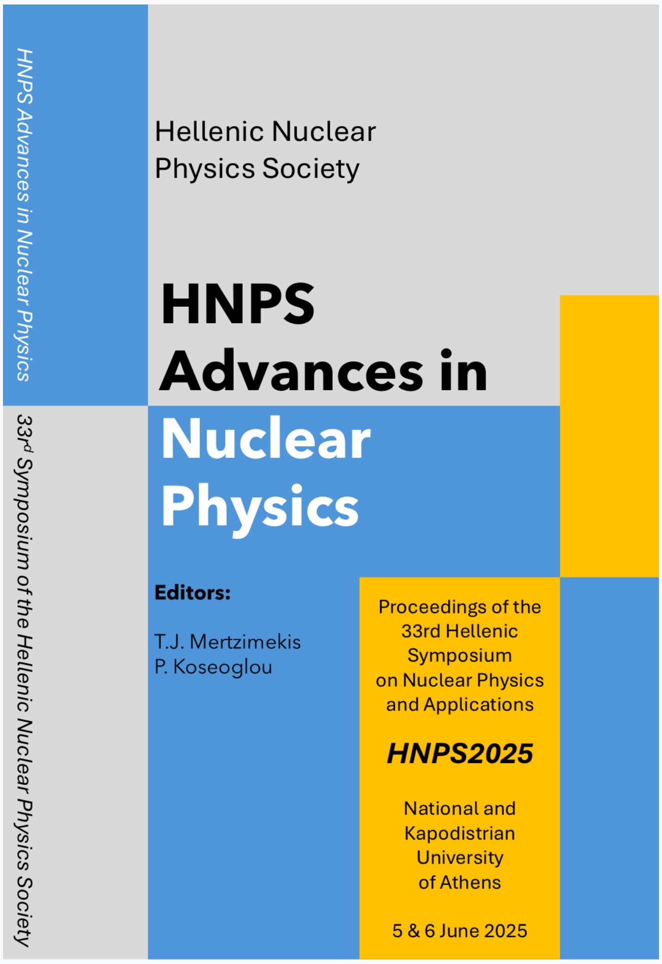

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ARTICLE

Diamond Detector Development for Neutron Measurements at the n_TOF Facility (CERN)

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Abstract
Diamond is a highly promising material for neutron detection due to its radiation hardness, fast response, and high signal-to-noise ratio. A single-crystal diamond (sCVD) detector with a ^{6}LiF conversion layer was developed in collaboration with CIVIDEC Instrumentation for in-beam neutron measurements in mixed field high-radiation environments at the n_TOF facility at CERN. The effect of the diamond detector thickness on the response to γ-rays was studied with a ^{137}Cs source. Additionally, measurements with thermal neutrons at the TRIGA reactor (Atominstitut Vienna) confirmed the proper detection of the recoils of the ^{6}Li(n,t)^{4}He reaction, by the developed detection system. In-beam tests at the EAR2 experimental area demonstrated stable performance under a white neutron beam, while the final measurement at the NEAR station validated the detector's suitability for neutron flux characterization in challenging high-radiation environments.

Keywords: Diamond detector; white neutron beam; thermal neutrons; NEAR station; EAR2

1. Introduction

Diamond sensors, constructed with the CVD technology [1], have emerged as a preferable choice for neutron detection due to their high radiation hardness and exceptional electrical properties [2]. Their high energy resolution, high signal-to-noise ratio, and exceptional thermal conductivity make them particularly suitable for measurements in harsh environmental conditions in terms of radiation.

These characteristics are especially relevant at the NEAR station of the n_TOF [3] facility at CERN, described in Section 3. This facility provides a mixed-field beam dominated by neutrons, produced by spallation reactions of 20 GeV protons impinging on a thick lead target. Due to its proximity, only 3 m to the spallation target, the NEAR station presents a highly challenging radiation environment, for the operation of an active neutron monitor.

A diamond detector system with dedicated electronics was developed by CIVIDEC Instrumentation GmbH [4] and implemented for the commissioning of the NEAR station, i.e. the characterization of the neutron beam flux and profile. Since neutron environments are often accompanied by intense γ-ray backgrounds, minimizing γ-ray sensitivity is essential for accurate neutron measurements; therefore, the detector's response to γ-rays was first studied to determine the optimal sensor thickness. It was then equipped with a 1.8 µm ^{6}LiF conversion layer (95% ^{6}Li-enriched) and tested with a thermal neutron beam at the TRIGA reactor (Atominstitut Vienna) [5, 6], to validate the proper detection of the ^{6}Li(n,t)^{4}He reaction recoils. Subsequently, the detector was installed at the EAR2 experimental area of n_TOF, to assess its response to a white neutron beam, and finally at the NEAR station for the main measurement campaign. The outcomes of these studies, together with the first results from the in-beam neutron measurements, are presented and discussed.

2. Detector Characterization at the Atominstitut Vienna

2.1 Gamma rays

In neutron irradiation, the presence of a γ-ray background presents a major obstacle for the precise determination of thresholds required for clear neutron–γ signal discrimination. Reducing the effective sensor thickness offers a potential means of minimizing this background. To investigate this effect, an experimental study was carried out using single-crystal diamond (sCVD) detectors of three different thicknesses: 50 µm, 140 µm, and 500 µm. The detectors were irradiated with a ^{137}Cs γ-source (661.6 keV), and the corresponding spectra are shown in Fig. 1. As expected, the interaction probability with γ-rays as well as the deposited charge, increases with detector thickness. For the 500 µm sensor, the Compton edge at 0.48 MeV is clearly visible, while it is absent in the thinner detectors.

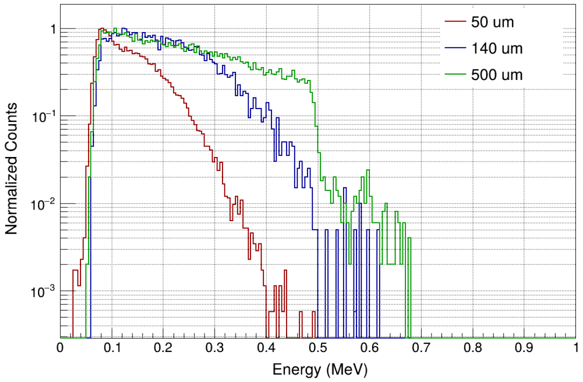

Figure 1. Experimental γ-ray spectra with a ^{137}Cs source for a 50 µm, 140 µm and 500 µm sCVD.

These measurements confirm that increasing detector thickness leads to higher energy deposition and consequently greater contamination from γ-ray interactions, consistent with simulation results reported in [7]. Based on these findings, a 50 µm diamond detector or smaller can be selected for the experiment, as it minimizes contributions from γ-rays. Furthermore, simulations performed with Geant4 for fast neutrons, as reported in [8], demonstrate that a 50 µm diamond detector offers an optimal balance between neutron sensitivity and minimization of the γ-ray background. Based on these results, the 50 µm detector was selected for the subsequent experimental campaign.

2.2 Thermal neutron beam

Since the detector is intended for neutron measurements with a white neutron beam using a ^{6}LiF converter, it was essential to first investigate its response to a well-characterized thermal neutron field in order to study the detection of the ^{6}Li(n,t)^{4}He reaction and validate the detector's geometry, based on the comparison with simulations. For this purpose, the detector was tested with thermal neutrons at the TRIGA reactor of the Atominstitut in Vienna. The 50 μm diamond detector, equipped with a ^{6}LiF conversion layer, was positioned at the exit of the reactor beam line, as illustrated in Fig. 2. The detector was operated at a bias voltage of -50 V, corresponding to an average electric field of $< E >= 1$ V/μm. The measured triton and alpha signals, along with a comparison to GEANT4 simulations, are presented in Fig. 3. The simulated thermal neutron beam was considered monoenergetic with an energy of 25.3 eV and the flux was approximately $1.5 \cdot 10^4$ n/cm^2/s.

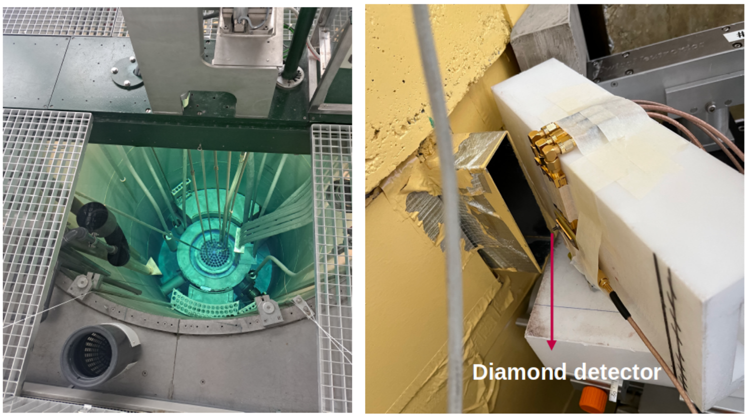

Figure 2. Experimental set-up for thermal neutrons measurement at the TRIGA II reactor at the Atomistitute, Vienna

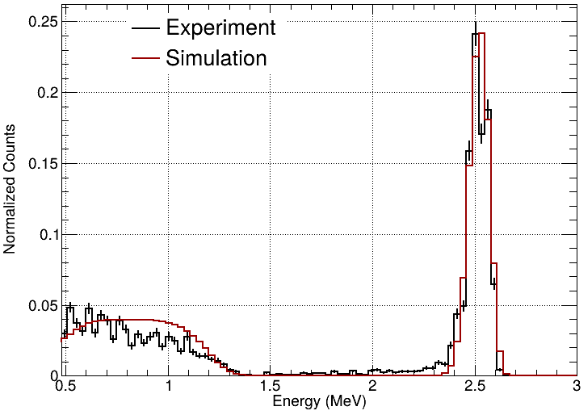

Figure 3. Experimental results of the ^{6}Li(n,t)^{4}He reaction recoils, collected with a beam of thermal neutrons, compared with Geant4 simulations.

A distinct triton peak is observed at approximately 2.5 MeV, while the alphas extend up to 1.3 MeV, in good agreement with the simulated spectrum. This consistency confirms that the detector geometry and material configuration were correctly implemented in the simulations. The geometrical detection efficiency for the tritons was determined from the Geant4 simulations to be 4.45% with a statistical error of $9 \cdot 10^{-5}$.

3. The n_TOF Facility at CERN

At the neutron time-of-flight (n_TOF) facility at CERN [9], a pulsed 20 GeV proton beam delivered by CERN's Proton Synchrotron (PS) impinges on a lead spallation target [10], producing a white neutron beam spanning more than eleven orders of magnitude in energy. The facility offers three experimental areas with different characteristics: the two main time-of-flight beam lines, EAR1 (operational since 2001, horizontal) [11] and EAR2 (since 2014, vertical) [12], with flight paths of approximately 185 m and 20 m, respectively, as well as the recently constructed NEAR station (commissioned in 2021) [3], located only 3 m away from the spallation target. A schematic representation of the n_TOF facility is shown in Fig. 4.

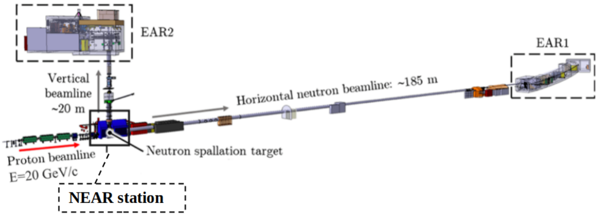

Figure 4. The n_TOF facility at CERN.

The long flight paths of EAR1 and EAR2 provide a very good energy resolution for the incoming neutrons, allowing a precise determination of neutron energies. In contrast, the NEAR station, due to its close proximity to the spallation target the separation of neutron energies becomes challenging, due to the poor neutron energy resolution. At the exit of the NEAR collimator, the neutron flux reaches about $1.5 \cdot 10^9 n/cm^2$ per standard proton pulse of $7 \cdot 10^{12}$ protons, approximately two orders of magnitude higher than EAR2, resulting in a difficult radiation environment.

The NEAR station is primarily designed for activation cross-section measurements of astrophysical interest; most experiments therefore rely on activation techniques [13], as well as material irradiation for engineering studies and any measurement with an active detector poses a serious challenge.

3.1 EAR2

The next in-beam measurement of the diamond detector was carried out at the n_TOF EAR2 experimental area, which features a 20 m vertical flight path from the spallation target. The neutron flux at EAR2 is well characterized both experimentally [14] and through detailed simulations [12], making it an ideal location to perform the first test of the diamond detector as well as the amplifier developed and produced by CIVIDEC Instrumentation GmbH [4]. This setup was used to study the detector response to the ^{6}Li(n,t)^{4}He reaction and to optimize its configuration for operation under the high rate conditions of the NEAR station.

The experimental setup is shown in Fig. 5. The diamond detector, equipped with the ^{6}LiF conversion layer, was positioned at the center of the neutron beam axis and enclosed in an aluminum shielding. A 1 m cable connected the detector to a CIVIDEC C2 spectroscopic amplifier of a bandwidth of 2 GHz and gain 40 dB. The amplifier was especially developed and produced by CIVIDEC Instrumentation GmbH [4] in order to withstand the high rate of the NEAR station. It's output then was then connected to the n_TOF Data Acquisition System. The detector was operated at a bias voltage of -50 V, similar to the thermal neutron measurement mentioned at 2.2.

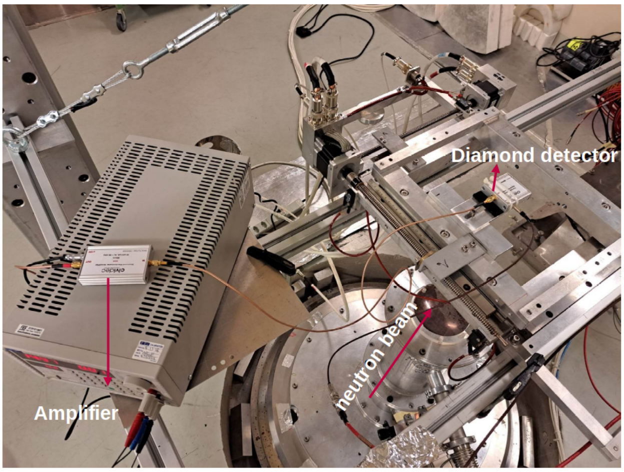

Figure 5. Experimental set-up at EAR2 at the n_TOF facility at CERN.

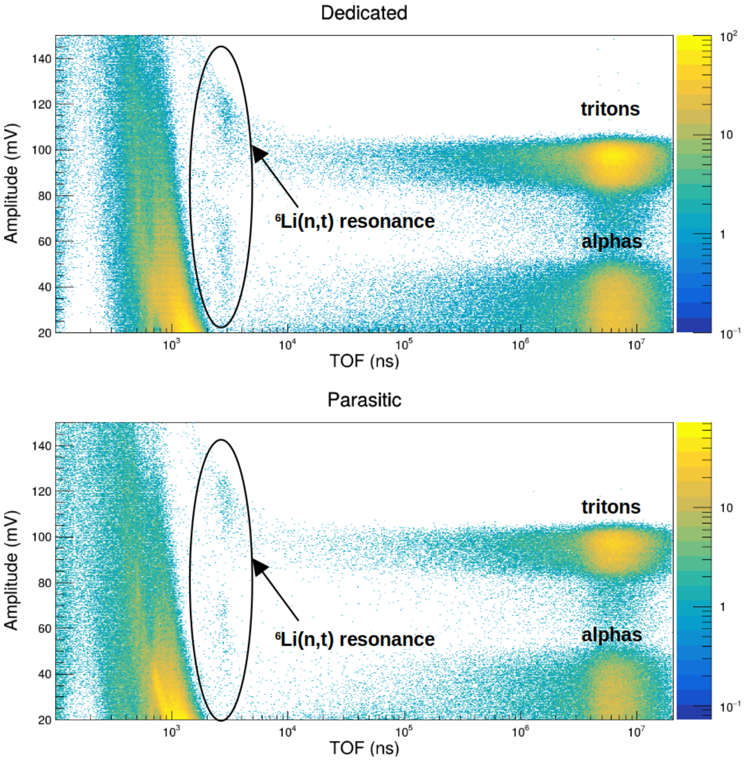

Figure 6. Two-dimensional histograms of the amplitude signal as a function of time of flight for EAR2, for the dedicated and parasitic beam intensity.

This initial measurement aimed to assess the operational performance and neutron detection capability of the diamond detection system under realistic beam conditions, as a preparatory step for the main experiment at the NEAR station.

The results of this test are shown in Fig. 6, which represents the two-dimensional histograms of the signal amplitude as a function of the time of flight (TOF). The measurements were performed with two proton beam intensities: a *dedicated* pulse corresponding to 8.5×10^{12} protons per pulse (ppp), and a *parasitic* pulse with approximately half that intensity (4.5×10^{12} ppp). The triton peak is clearly observed between 80 mV and 120 mV, while the alpha particles appear up to about 50 mV, consistent across both beam intensities. Due to the relatively long flight path, 20 m, a clear separation between triton and alpha peaks is evident at higher TOF values (i.e., lower neutron energies). Around a TOF of 2×10^3 ns, corresponding to a neutron energy of roughly 200 keV, the characteristic ^{6}Li(n,t)^{4}He resonance is also visible for both beam conditions.

3.2 NEAR Station

Following the experimental campaign at EAR2 and the work reported in [15], the diamond detector was then installed at the NEAR station. Located less than 3 m from the lead spallation target, the NEAR station is in an intense radiation environment, making any measurement with an active detector particularly challenging.

The detector signal must be transmitted over long distances, specifically through a 70.8 m cable to reach the Data Acquisition (DAQ) system. To quantify the signal degradation introduced by this long cable, a characterization test was performed. A 2 ns wide pulse was generated at the DAQ location using a pulser, sent to the NEAR station, and reflected back. The resulting waveform, shown in Fig. 7, exhibited a loss of 41.5% in amplitude and an increase in full width at half maximum (FWHM) by a factor of 2.5, indicating a substantial deterioration in signal quality compared to that observed at EAR2. This effect is also shown in Fig. 8, which compares the FWHM of the triton signals measured at EAR2 and at the NEAR station. Although the setup is not identical to the pulser comparison, since at EAR2 a 20 m cable connects the amplifier to the DAQ, whereas at NEAR a 70.8 m cable is used, the experimental signals clearly show a broadening, with the FWHM increasing by a factor of approximately 2.8.

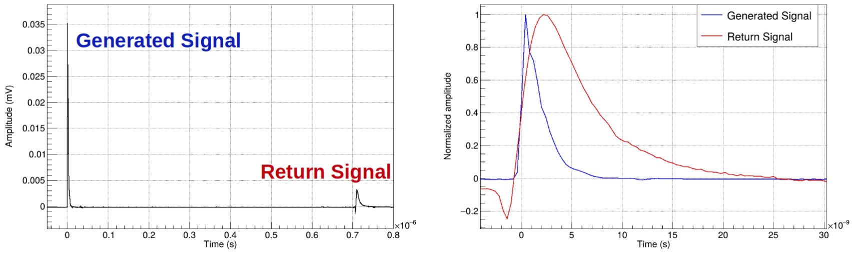

Figure 7. Cable calibration at the NEAR station of the n_TOF facility at CERN.

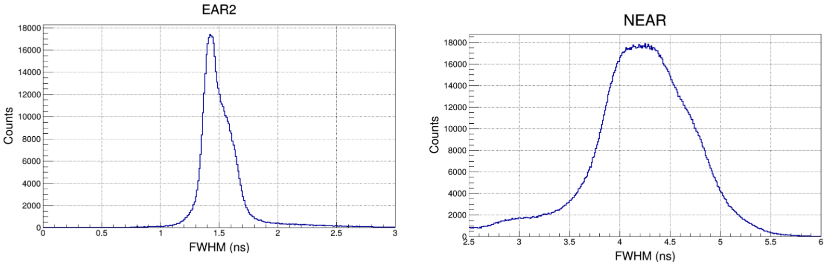

Figure 8. FWHM of the signals for time of flights between 10^6 ns and 10^7 ns for EAR2 and the NEAR station.

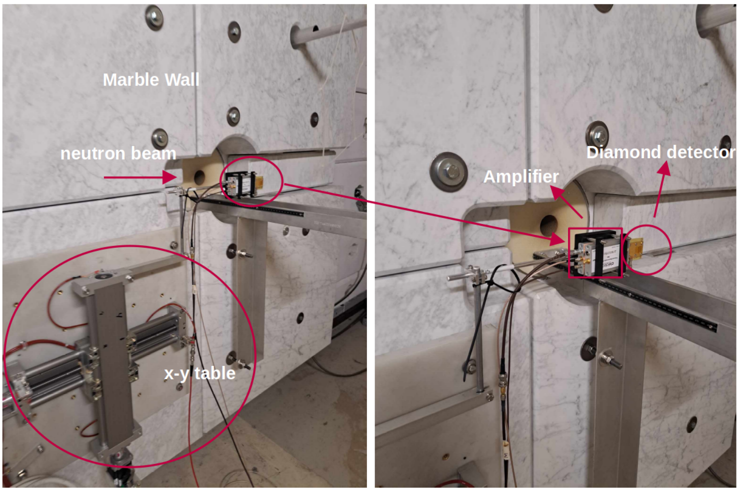

Figure 9. Experimental set-up at the NEAR station at the n_TOF facility at CERN.

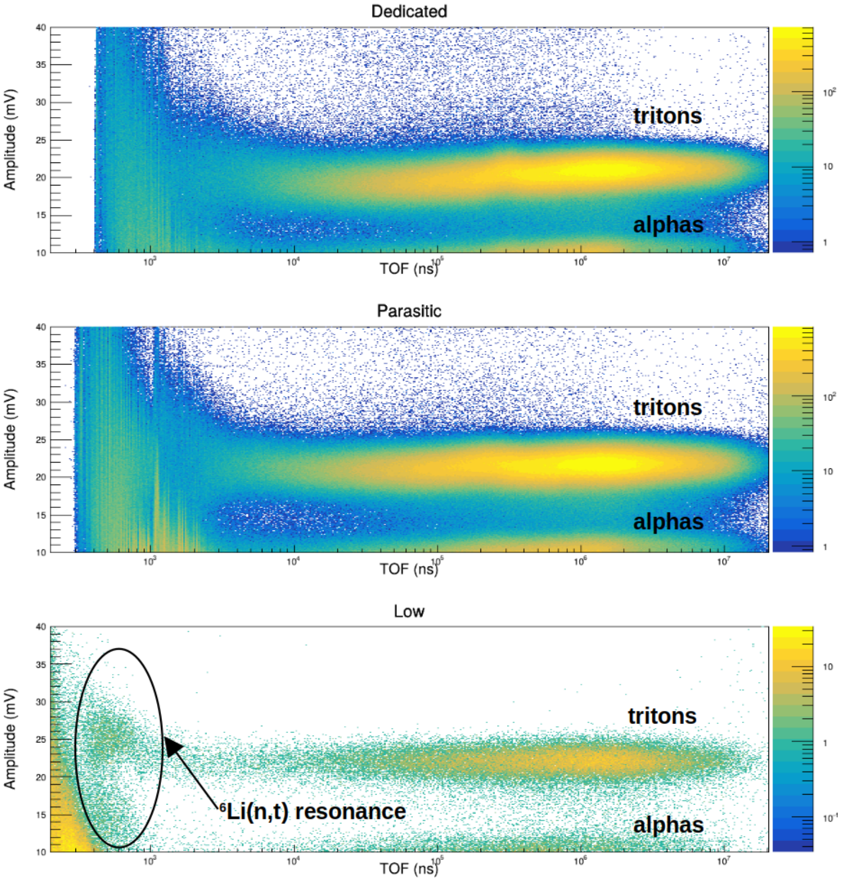

Figure 10. Two-dimensional histograms of the amplitude signal as a function of time of flight for NEAR, for the dedicated, parasitic and low proton beam intensity.

The experimental setup is shown in Fig. 9. The diamond detector, equipped with a ^{6}LiF conversion layer, was positioned 12 cm from the marble shielding wall and approximately 32 cm from the collimator exit, aligned parallel to the neutron beam axis. The same bias voltage and the same CIVIDEC C2 spectroscopic amplifier (bandwidth 2 GHz, gain 40 dB) used in the EAR2 campaign were employed, with the amplifier directly connected to the detector. The amplified signal was then transmitted through the 70.8 m cable to the DAQ system.

The results are shown at Fig. 10. In addition to the two main proton beam intensities, measurements were also performed with *low* intensity pulses of approximately 10^{10} ppp. For the *dedicated* and *parasitic* proton beams, significant signal saturation is observed up to TOF values of about 2×10^3 ns (corresponding to > 8 MeV neutron energies). However, for the low-intensity pulses, the ^{6}Li(n,t)^{4}He resonance becomes visible, demonstrating the detector's capability to measure higher neutron energies under reduced beam intensity. The amplitude of the triton peak is notably lower compared to EAR2, mainly due to signal attenuation along the ~80 m cable. Moreover, the broader energy distribution is attributed to the reduced time-of-flight resolution of the NEAR station caused by its short flight path.

Overall, these results are encouraging, demonstrating for the first time that the diamond detector can successfully measure the neutron beam at the NEAR station through the ^{6}Li(n,t)^{4}He reaction.

4. Conclusions

A 50 μm single-crystal diamond (sCVD) detector equipped with a thin ^{6}LiF conversion layer and a 2 GHz very fast charge amplifier, were developed for in-beam neutron measurements at the NEAR station of the n_TOF facility.

The detector was first characterized with a ^{137}Cs source to study the effect of thickness on γ-ray sensitivity, confirming that thinner sensors effectively minimize γ-ray interactions. Subsequent tests with thermal neutrons at the TRIGA reactor (Atominstitut, Vienna) validated the proper detection of the ^{6}Li(n,t)^{4}He reaction, in good agreement with GEANT4 simulations.

The next in-beam measurement was performed at the n_TOF EAR2 experimental area, with a flight-path of 20 m, demonstrating that the diamond detector can efficiently measure the white neutron beam via the ^{6}Li(n,t)^{4}He reaction. The main experiment was then conducted at the NEAR station, located only 3 m from the spallation target, where the detector operated successfully in the harsh radiation environment and significant signal attenuation due to long transmission cables. While the dedicated and parasitic pulses exhibited saturation at high neutron energies, the low proton beam intensity pulses allow the discrimination of higher neutron energies, due to the much lower g-flash and neutron pile-up. These results confirm the suitability of the detector for neutron flux characterization in environments with extremely high instantaneous flux and intense γ-ray backgrounds. The developed detection system will be used for the characterization of the neutron flux and beam profile of the NEAR station.

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Instrumentation GmBH.

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