EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Study of semiconductor detectors' performance at NEAR

08.01.2025

M. Diakaki[1], M. Bacak[2], C. Weiss[2,3], E. Griesmayer[2,3], K. Kaperoni[1], M. Kokkoris[1], J. Bartolomé[4], Z. Eleme[5], V. Foteinou[5], C. Guerrero[4], D. Hainz[2], E. Jericha[2], S. Kopanos[1], I. Kopsalis[1], V. Michalopoulou[1], N. Patronis[5], A. Reina[4], R. Vlastou[1]
and the n_TOF Collaboration[6]

[1]National Technical University of Athens, Greece
[2]TU Wien, Atominstitut, Stadionallee 2, 1020 Wien, Austria
[3]www.cividec.at
[4]Universidad de Sevilla, Spain
[5]University of Ioannina, Greece
[6]www.cern.ch/n_TOF

Spokesperson(s): M. Diakaki (diakakim@mail.ntua.gr), M. Bacak (michael.bacak@tuwien.ac.at)
Technical coordinator: O. Aberle (oliver.aberle@cern.ch)

Abstract

We propose to measure the degradation of thin active semiconductor detectors in the n_TOF NEAR mixed field beam. In our previous work, focused on characterizing the neutron beam at the NEAR station employing a thin diamond detector, we demonstrated that these devices can be used at NEAR and obtained good understanding of the spontaneous counting rates and gamma-flash behavior. During the previous measurement campaign, effects of detector degradation were observed which we propose to further investigate as those results indicate radiation damage mainly of the sensor material, e.g. the diamond itself, not excluding some damage in the passive electronics as well. The potential to measure this degradation with increasing dose/neutrons is of interest for applications of future detectors at NEAR and other harsh radiation environments. Furthermore, we propose to extend this study beyond diamond, i.e. to silicon carbide (SiC) as a promising sensor material for different applications in the future.

Requested protons: 1.2E19 protons on target, (split into 2 runs of 6E18)
Experimental Area: NEAR

1 Introduction

The NEAR station of the n_TOF facility has been built at a very short distance from the Pb spallation target (approximately 2.5 m) to take advantage of the very high neutron fluence and to perform various challenging measurements both for applications [1] and fundamental research [2]. The former include integral measurements relevant to nuclear energy production studies (fission and fusion), irradiation of various materials for radiation damage studies (MGy doses) etc. The latter include activation measurements of extremely small-mass samples and radioactive isotopes and/or of very low reaction cross sections for nuclear astrophysics [3].
The neutron beam enters the NEAR station through the movable shielding wall of the newly built target-moderator assembly with the possibility to use a suitable filter to exclude certain energy ranges of the white neutron energy spectrum. The design development and technical characteristics can be found in [4].
The neutron beam of NEAR has gained a lot of interest and has been commissioned and characterized both experimentally and via extensive Monte Carlo simulations by independent groups and techniques. To date, the multiple foil activation technique [7], the moderation-absorption technique [7], active diamond detectors [5,6] and well characterized electronics [1] have been used to characterize the neutron beam, and the background levels have been measured [8] in order to exploit in the most efficient way this new station.
The first attempt to perform in-beam measurement of the neutron flux and beam profile at NEAR was proposed and successfully completed very recently by the n_TOF collaboration [5,6], with use of a specially developed 50 μm thick diamond detector and electronics setup. Due to its excellent electrical and physical properties diamond is considered one of the most promising detector materials in harsh environmental conditions (fission and fusion reactors, high energy physics experiments). The necessary detector and electronics development was undertaken by colleagues at CIVIDEC Instrumentation [9]. The results of the experiments were successful, proving this detector to be a powerful tool to perform in-beam measurements at NEAR. The corresponding analysis along with the necessary Monte Carlo simulations are currently under finalization in the context of a PhD thesis.
However, after long exposure in the NEAR station, an interesting degradation of the detector's recorded signals was observed (see section 2). As a continuation of the previous measurements, we propose to properly study this degradation of the thin single-crystal diamond performance due to radiation effects with in-beam and offline EPR measurements while also decoupling the different sources of damage and quantitatively estimate the lifetime at NEAR. Despite radiation resistance being an important requirement for the usage of diamond sensors as neutron beam monitor detectors for various applications, up to now it has been poorly studied for single-crystal detectors [e.g. [10] and references therein]. The estimated lifespan for 50 μm diamond thickness is $\sim 10^{15}$ (14 MeV neutrons)/cm2 [10] but has not been experimentally proven.
Furthermore, we also propose to extend our study to another promising sensor material for harsh environmental conditions, namely silicon carbide (SiC). SiC is currently being extensively studied as a possible replacement of Si in various applications, including high energy physics experiments at CERN. Thus, the proposed radiation damage study with in-beam and offline measurements is currently of high interest [11-12].

2 Overview of the previous experiments

The basic idea of the setup proposed in [5] was realized and already successfully used for the measurement of the neutron beam fluence and profile at NEAR. The detector prepared by CIVIDEC Instrumentation contains a 4 mm x 4 mm x 50 µm single-crystal diamond sensor, fabricated via chemical vapor deposition, facing a foil with a ^{6}LiF deposit (Figure 1-top panel). A typical setup is shown in the bottom panel of Figure 1.

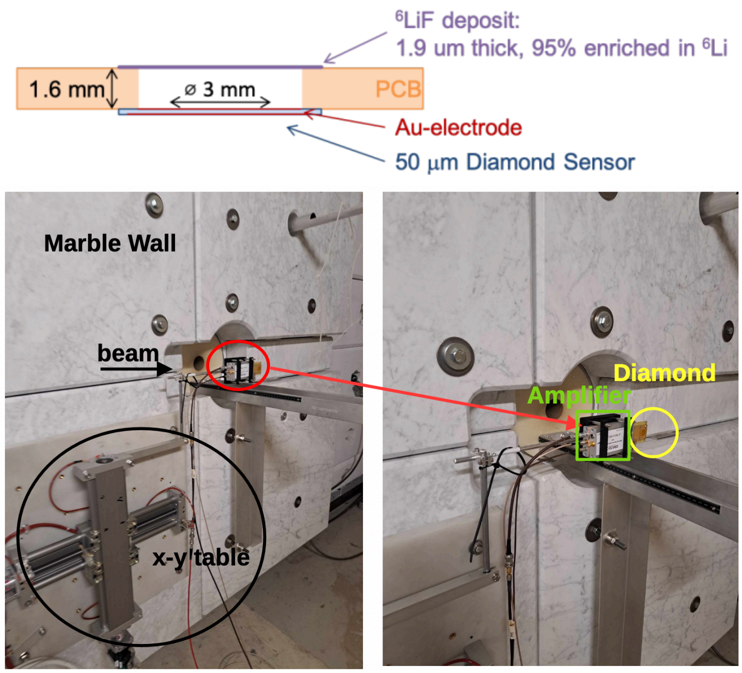

Figure 1: Top panel: Detector schematics. Bottom panel: A typical measurement setup with the diamond detector in-beam, in front of the exit of the collimator at NEAR, and the amplifier directly connected to it. The x-y table was used to remotely move the detector perpendicularly to the beam axis and measure the neutron beam spatial distribution.

The neutron flux at NEAR spans several orders of magnitude in energy and the neutron detection method depends on the energy of the incoming neutron. The fast neutrons (> 1 MeV) were detected via the energy deposition of the recoil nuclei from the elastic and inelastic scattering and the ^{12,13}C(n,xα/p) reactions with the ^{12,13}C nuclei. Low energy neutrons were detected using the ^{6}Li(n,t)^{4}He standard reaction.

Furthermore, three different readout configurations were used in different measurement campaigns. The first one was with the use of a 10 MHz DC-coupled amplifier (“C8”), the second one with a 2 GHz AC-coupled 40 dB amplifier (“C2”) and the third one without any preamplification stage (“Direct”). The first and third configuration aimed for the detection of the high neutron energy region while the third one was mainly used for the detection of lower energy neutrons, since the g-flash was saturating the preamplifier for dedicated and parasitic n_TOF pulses above ~0.3 MeV (i.e. 4-8 E12 ppp). The three configurations showed very good agreement, see Figure 2. Overall, the measurements were successful and some of the preliminary results are shown in Figure 2.

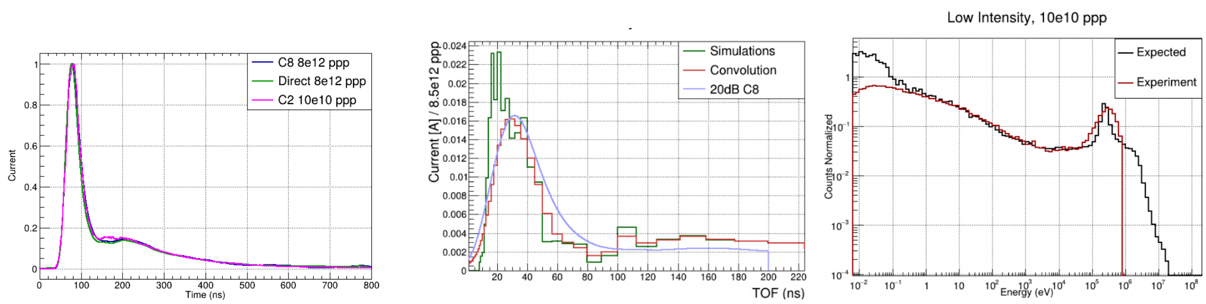

Figure 2: Left panel: Very good agreement between the response to the NEAR beam with three different electronics used. Middle panel: Comparison between expected (Simulations/Convolution) and experimentally ("20 dB C8") obtained results. Right panel: Comparison of expected and experimentally obtained counts from ^{6}Li(n,t) with the C2 amplifier, also showing the ^{6}Li(n,t) resonance around 250 keV (preliminary).

Most measurements were performed with the fast C2 amplifier allowing to record individual signals from the ^{6}Li(n,t) reaction. Continuous recording of the detector signal allowed to observe the evolution in the signal characteristics. With increasing irradiation, we observed a continuous change in the signals' characteristics which is likely to be interpreted as radiation damage. As shown in Figure 3, degradation was observed in the signal's resolution (increase in FWHM), and a decrease of the charge collection efficiency (decrease of area). Nevertheless, the counting rate from the recorded triton counts was not affected throughout the measurements.

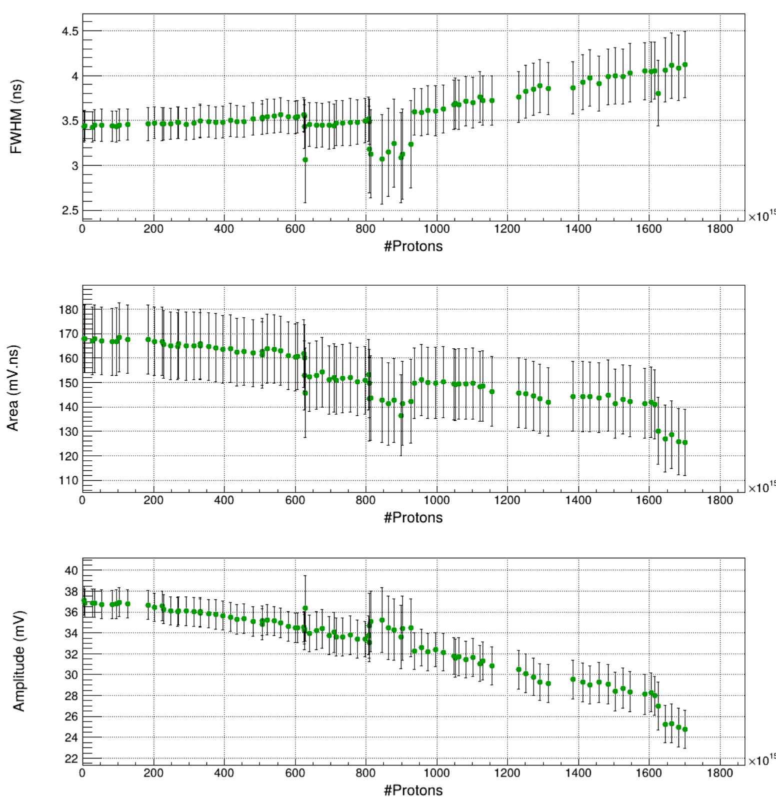

Figure 3: Characteristics of the recorded ^{3}H pulses from the ^{6}Li(n,t)^{4}He reaction over protons on target. The discontinuities in the histograms, e.g. around 6.2e18 and 8.5e18, correspond to changes in the DAQ settings (e.g. change of pulse height resolution).

The results of Figure 3 correspond to one of our campaigns. We also measured in other campaigns but since a) the setup slightly changed each time, b) the neutron beam profile at NEAR was measured, and c) the detector was used at other measurements (EAR1, EAR2), the conversion from protons on n_TOF target to neutrons on detector is not straightforward. Consequently, the combination of all the campaigns would not give a consistent study of the radiation damage effects with respect to neutron dose, this is why a new campaign is proposed.

3 New experimental setup & proton request

In our previous experiments, the radiation damage is mainly caused by two sources. Fast neutrons directly interact elastically/inelastically/through nuclear reactions with the carbon nuclei of the diamond and the energy deposition of the recoil nuclei is therefore homogeneous throughout the thickness of the sensor. Damage induced by slow neutrons origins from the alpha and triton recoils of the ^{6}Li(n,t)^{4}He reaction which deposit their full energy in the detector volume, creating "layers" of increased damage at the end of range. The effects of these two kinds of damages can be substantially different.
In order to decouple these two distinct effects, we propose to measure with two 50 μm thick new diamond sensors in parallel, one with and one without ^{6}LiF converter.
The proposed setup per detector is schematically illustrated in Figure 4. In order to obtain the maximum information possible, we aim to split the detector signal and continuously record in parallel the following outputs: a) AC output without amplification (V_{LG}) and therefore no saturation in the fast neutron energy region (n_TOF DAQ), b) AC output with a C2 amplifier (V_{HG}) to monitor the signals from the ^{6}Li(n,t) reaction (n_TOF DAQ), c) slow DC measurement of the dark current as an indication of the radiation damage of the sensor.

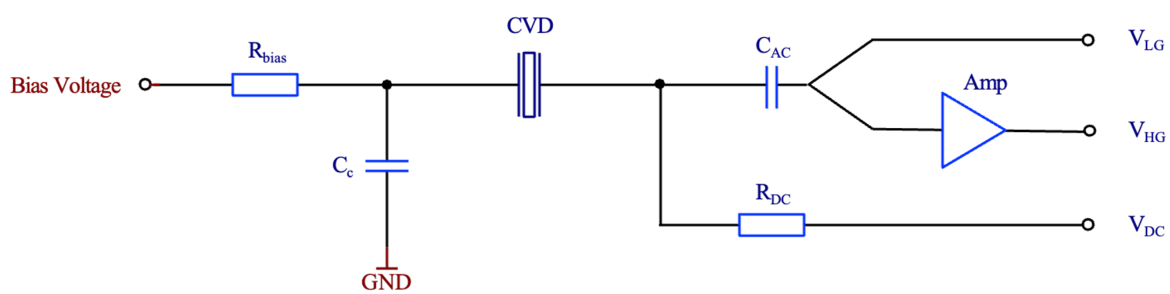

Figure 4: Schematic illustration of the detector and electronics. Three different outputs will be recorded in parallel a) AC output with low gain (V_{LG}) for high neutron energies and the g-flash region, b) AC output with high gain (V_{HG}) for the recording of signals from the ^{6}Li(n,t) reaction at low neutron energies and c) dark current of the sensor (V_{DC}).

Finally, in order to characterize the defects in the sensor material we plan to perform, after the end of the irradiation campaign, Electron Paramagnetic Resonance (EPR) spectroscopy measurements, which is a powerful tool for studying the physical and chemical structure of point defects in crystalline semiconductors, at the NSCR "Demokritos", Greece [13,14].

In summary, we aim to study the radiation hardness of thin single-crystal diamond detectors at the NEAR neutron beam. This study will quantify the lifetime of this detector material as a neutron beam monitor at NEAR, disentangle the two distinct effects of radiation damage, and will also lead to more general results on the radiation damage of diamond detectors when used as fast/slow neutron monitors in mixed fields. The proposed in-beam measurements of the performance with three different output recordings in parallel at NEAR will allow to consistently study the damage over slowly increasing doses. Offline EPR measurements will allow for the study of the structure defects.

Extrapolating from Figure 3, we estimate a total loss of the triton signal (amplitude) in the detector's noise after ~5E18 protons on target. As one of the detectors in the setup will not have the ^{6}LiF converter and therefore have, in theory, less radiation damage, we request 6E18 protons on target for the measurement with the diamond detectors.

We intend to replicate this study also with thin SiC sensors in the same configuration. Installing the four detectors at the same time is not feasible due to the slightly too narrow NEAR beam diameter of 6 cm diameter which would lead to inhomogeneous illumination of the sensors and subsequent space constraints for electronics. Hence, we also request, for a second campaign, another 6E18 protons on target for the SiC detectors, resulting in a total of 1.2E19 protons on target.

Summary of requested protons: 1.2x10^{19}

References:

[1] M. Cecchetto et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 8, AUGUST 2023

[2] A. Mengoni et al., CERN-INTC-2020-073; INTC-I-222 (2020)

[3] E. Stamati, A. Manna, G. Gervino et al., CERN-INTC-2022-008; INTC-P-623 (2022)

[4] M. Ferrari et al., Phys. Rev. Accel. Beams **25**, 103001 (2022)

[5] M. Diakaki, M. Bacak et al., CERN-INTC-2022-022 / INTC-P-631 (2022)

[6] K. Kaperoni et al., RAP CONFERENCE PROCEEDINGS, VOL. 8, PP. 79–83, 2023

[7] E. Stamati et al., EPJ Web of Conferences **284**, 06009 (2023)

[8] J. Lerendegui-Marco, M. Bacak et al., CERN-INTC-2022-018 / INTC-I-241 (2022)

[9] CIVIDEC Instrumentation, https://cividec.at/

[10] M. Passeri et al., Nuclear Inst. and Methods in Physics Research, A 1010 (2021) 165574

[11] T. Gaggl et al., Nucl. Inst. and Methods in Phys. Res. A 1040 (2022) 167218

[12] A. Gospner et al., 2023 JINST 18 C11027

[13] M. Kokkoris et al., Nucl. Inst. and Methods in Physics Research B 195 (2002) 414–421

[14] G. Mitrikas, M. Kokkoris et al., Eur. Phys. J. AP 21, 163–170 (2003)

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using NEAR rail, NEAR DAQ	☐ To be used without any modification ☐ To be modified
Standard Diamond and SiC detectors and electronics as well as detector supports adapted to NEAR rail	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]	

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m^3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[50] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
	Laser	☐	[laser], [class]

Non-ionizing radiation Safety	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			