n_TOF: DEVELOPMENTS OF NEW DIAGNOSTIC METHODS FOR FAST AND THERMAL NEUTRONS BASED ON TIMEPIX AND GEM DETECTORS

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1 Introduction

Our research activity was born from a collaboration between ENEA and INFN in Frascati and this report outlines the main results obtained in the last year. Our work can be divided in two main research lines: support for the measurements and optimization of the neutron beams on the n_TOF experimental areas EAR1 and EAR2, and characterization of new neutron detectors for nuclear fusion, radio-protection and medical applications. In the framework of nuclear fusion, our group carries out an activity related to the development of compact detectors for fast neutron monitoring and for the study of neutron-induced reactions of interest in the field of nuclear fusion. A further improvement has been achieved for thermal neutron detection using LiF and B_4C converters. These have important applications in thermal neutron radio-protection and as monitor of neutron beams. In the last year, a new collaboration started with LENA (Applied Nuclear Energy Laboratory) of Pavia University. The collaboration concerns the monitoring of ^{10}B concentration for Boron Neutron Capture Therapy (BNCT). First results have been developed in a degree thesis [1], and, for sake of brevity, the reader can refer to this work.

2 Neutron Facilities

In the framework of the n-TOF collaboration, our group actively participates both as support and as facility users. The n_TOF plant at CERN is a neutron spallation source and hosts a series of experiments dedicated to various applications relevant to basic nuclear physics, astrophysics, nuclear medicine and emerging nuclear technology: measurements of capture sections on radioactive samples, long-life fission fragments, capture and fission sections of minor actinides, necessary for nuclear waste transmutation projects and for the design of innovative nuclear systems, such as accelerator systems and fourth-generation fast nuclear reactors. n-TOF has two neutron beam lines with two measuring stations; in the first called EAR1 the beam arrives after travelling along a flight path of 185 m with a high instantaneous flux. In EAR1, the measure time of flight technique allow to measure neutron energy over a wide range with good resolution. At 12 m from the EAR1 station, there is the beam dump area that is often used for testing new detectors. In the second measuring station, called EAR2, the beam arrives after a trajectory of 19 m with a higher neutron flux in the position of the sample with respect to EAR1. The EAR2 station is dedicated to the study of short-lived isotopes. Neutron sources where our experiments are often conducted are FNG (Frascati Neutron Generator) and HOTNES at the ENEA Frascati research center. FNG is a neutron generator based on an electrostatic accelerator and produces 14.0 MeV and 2.5 MeV neutrons using the fusion reactions T(d,n)α and D(d,n)^{3}He, respectively. Neutron emission is isotropic and can reach an emission rate up to 10^{11} n/s. HOTNES is a passive neutron source based on moderated sealed neutron source AmB. The source of AmB has been incorporated in a polyethylene structure in order to obtain a uniform flux of thermal neutrons on circular planes of 30 cm in diameter with a peak energy of 25 meV. The main plane is localised a 50 cm from the AmB source with a neutron flux of 763 n/cm^2/s.

3 Neutron beam monitor at n-TOF

Before each experimental run, it is necessary to carry out the alignment of the neutron beam. Generally this is carried out using radiochromic films. Our group has supplied active 2D detectors based on quad 2×2 of Timepix1 silicon detectors: the covered area is 28×28 mm^2 with 512×512 square pixels of 55 μm side. The spectrum of neutron beams produced on n-TOF extends over several order of magnitude, ranging from thermal up to about 1 GeV (fig. 1) with fluxes higher than 10^4 n/cm^2/s.

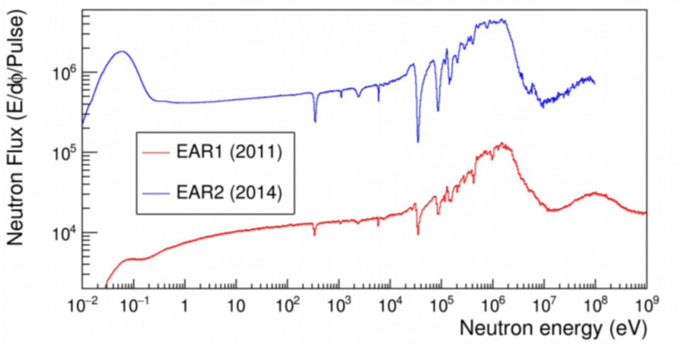
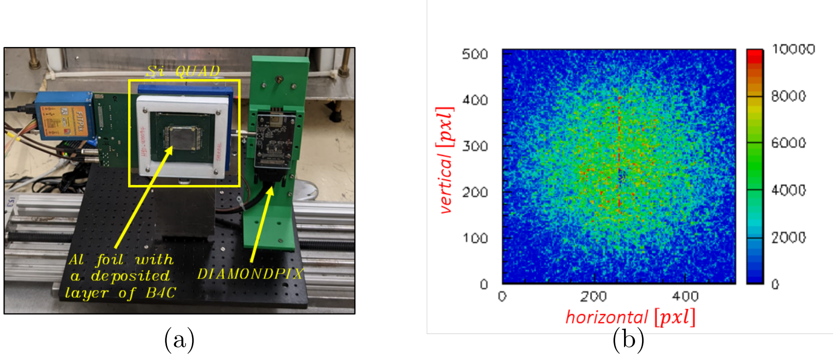


Figure 1: *Neutron spectra on the two experimental areas EAR1 and EAR2 of the n-TOF facility.*

In this case, the active material for neutron is a silicon layer having a thickness of 300 μm. Interaction of neutrons with silicon produces charge particles that are registered as cluster of pixels on the surface covered by quad. Timepix1 [2] has three different acquisition modes: counting, Time over Threshold (ToT) and Time of Arrival (ToA). This means that for each pixel, it provides the presence or not of a signal resulting from a particle interaction (counting mode), the released charge (ToT mode) and the time stamp when the interaction occurred (ToA mode) respect to a reference time (software or hardware trigger). The Timepix1 quad can only acquire in one of these modes at a time. A Timepix detector has already been successfully used at n-TOF to measure the spatial profile of the neutron beam [3]. Although silicon as an active material for neutrons has a low efficiency, the flux is high enough to obtain a beam image. This especially applies for some characteristic reactions of fast neutrons in silicon. In addition, it has also been used in combination with a polyethylene converter to increase efficiency to fast neutrons and with an ^{10}B converter to detect also low energy neutrons (fig. 2a and 2b).



(a) (b)

Figure 2: *a) experimental set-up showing the Si quad with B_4C converter and the Diamondpix detector; b) image of the neutron beam acquired with the Si quad.*

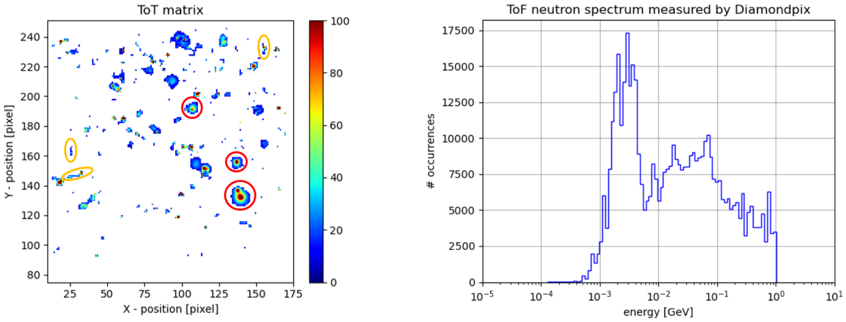
The good timing and particle identification properties of the Timepix have proven fundamental to collect virtually background-free data, with good spatial and time resolution. The Timepix ASIC can store charge, time, and position information with a maximum rate of about 5 MHz per pixel. The detector active area can cover easily the full size of the neutron beam, about 3 cm in diameter.

4 CVD diamond Timepix3 for fast neutrons

As is known, diamond is a radiation hard material and represents an excellent candidate in high radiation flux environments like those expected on modern fusion reactors. At the moment, our group is working on a new diamond detector realized by a coupling of diamond plate to a Timepix3 chip[5]: the "Diamondpix" [4]. Our first prototype is based on CVD diamond 500 μm in thickness and with an area of 10×10 mm^2. On one side, a matrix of small conductive pads have been deposited in order to realized a coupling to the Timepix3 chip through the bump-bonding technique. On the other side a 300 nm Gold layer has been deposited in order to obtain the polarization electrode. As a result, the Diamondpix is a 2D diamond detector with an area of about 1 cm^2 and pixels of 55×55 μm^2 as for standard semiconductor Timepix3 detectors. In addition, with respect to Timepix1, the Timepix3 chip can acquire simultaneously in counting, ToT and ToA modes and can reach time resolution down to 1.6 ns. Diamondpix has been characterized on the n-TOF facility by means of time-of-flight (tof) measurements. In this way it was possible to select specific energies by means of tof measurements and study its response in term of tracks morphology and charge. The energies of interest are those of fast neutrons produced on fusion reactors: from 1 to 20 MeV.

4.1 Morphology analysis and Time of Flight measurements

As shown in fig. 2a, Diamondpix was installed in the dump area after the EAR1 experimental area at a distance of 197 m from target where neutron beam is produced. It was polarized to 300 V and controlled by the katherine module via a long cable in order to not expose the control electronic to the neutron beam. Diamondpix has been triggered with an acquisition time of 150 ms. This value was enough to cover all the neutron spectrum in tof. Data taking has been performed in two different n-TOF runs: one week in May and about two weeks in November. In this case, interaction of a neutron in diamond produces a cluster of pixels, i. e. a 2D track, having a specific morphology and charge. Then it is possible define some morphological parameters and applying appropriate cuts on energy, it is possible to identify the tracks due to neutrons and discard those arising from the interaction of other particles particularly the gamma background (fig. 3a).



(a) (b)

Figure 3: *a) particle tracks observed on Diamondpix: red circles highlight some tracks from neutron interactions, yellow circles those from gamma interations; b) n-TOF spectrum reconstructed with Diamondpix in time-of-flight after neutron cluster selection.*

After discrimination of neutron tracks, the corresponding ToA measures allowed to get the neutron spectrum of the n-TOF neutron beam (fig. 3b). As expected, it can be observed that for energies less than 1 MeV, there is no signals because no significant reactions can be exploited for lower energy neutrons and the detector threshold cuts lower charges.

4.2 Charge energy measurements

The obtained tof spectrum has been used to identify some specific energies of interest for fusion (i.e. 2.5 and 14.0 MeV) to study the response of Diamondpix. At the moment, data analysis is ongoing and will be accurately refined in a PhD thesis. A significant result has been observed for the charge response for different selected neutron energies (fig. 4).

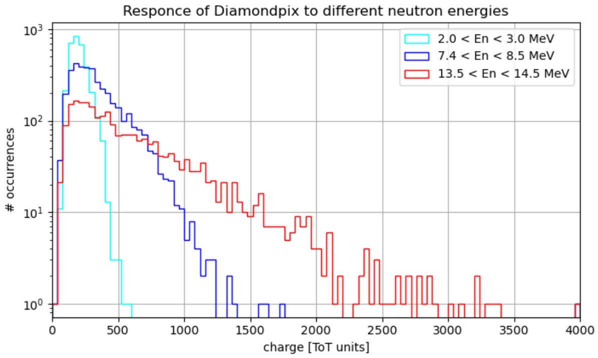
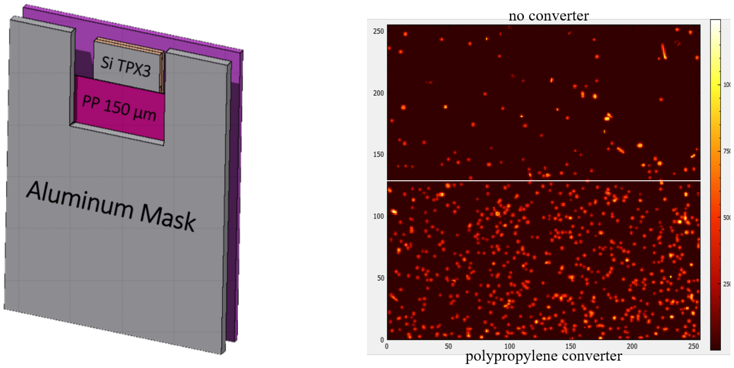


Figure 4: *Charge distributions observed for different neutron energies as selected from measured n-TOF spectrum.*

As can be observed, the increase of neutron energy produces a distribution of charge with increasingly broader edges. This particular charge distribution are expected as a consequence of elastic reactions of fast neutrons with ^{12}C. In addition the elastic cross section has an important weight, even when the total charge cross section increase and triggers reaction with charge particles productions. This applies especially in the energy range under investigation (1 - 20 MeV). A comparable distribution for 14 MeV neutrons has been observed at the FNG facility. In addition to carbon recoil reactions, the other important reactions that will be analyzed are ^{12}C(n,3α) and ^{12}C(n,α)^{9}Be. This last reaction is particularly significant because is exploited for spectroscopy of neutrons with energies higher than 5.7 MeV.

5 Si Timepix3 with polyethylene converter for fast neutrons

For the monitor of fast neutron, our group studied also the possibility to use a standard Silicon Timepix3 equipped with plastic converters in order to detect neutrons through the recoil protons. The first set-up has been realized with an Aluminum mask equipped with a 150 μm polypropylene foil placed at few mm from the detector surface because of the delicate wire bondings on the detector edges. The foil covers only one half of the surface in order to evaluate the effect of plastic converter (fig. 5a).



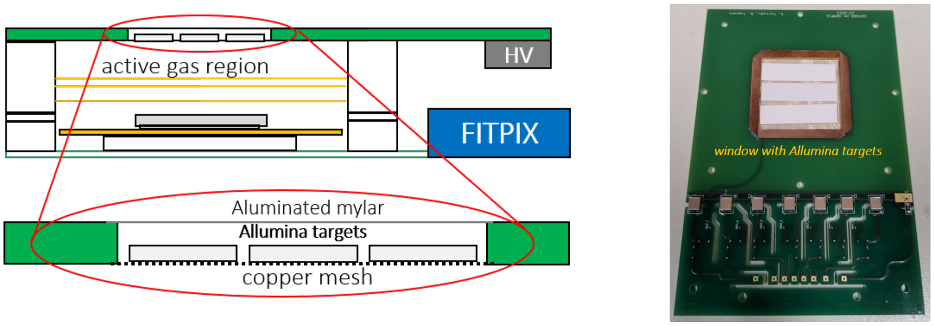
(a) (b)

Figure 5: *a) layout of the Silicon Timepix3 detector with Al mask and polyethylene (PP) converter foil; b) tracks of recoil protons after interaction of 2.5 MeV neutrons.*

First tests have been performed at the FNG facility with 2.5 MeV neutrons and the recoil protons has been clearly observed (fig. 5b). The shown tracks have been discriminated against the background gamma tracks.

6 A new GEMpix for measurements on charged reaction products

In the framework of the n-TOF collaboration, the activity proposed by the ENEA/LNF group is in the field of nuclear fusion and focalizes on the effects of radiation damage on structural materials constituting the inner part of Tokamaks, especially in the blanket and divertor which are subjected to extremely high neutron fluxes. Particularly important are the reactions (n, cp), that is reactions with production of light charged particles such as protons, deutons, tritium and alpha particles, responsible for the production of hydrogen and helium. The presence of these elements determines a change in the thermo-mechanical bonds of the structural elements and a consequent embrittlement of the structures. Within this research program, the ENEA/LNF group has developed a new GEMpix detector [6] to optimize the acquisition parameters in the study of reactions (n, cp). The proposed GEMpix has a standard configuration: a triple GEM camera read by a Timepix1 quad (fig. 6). The innovative element consists of the entrance window that must accommodate the targets of the specific material of which you want to study the reaction (n, cp).



(a) (b)

Figure 6: *a) layout of the Silicon Timepix3 detector with Al mask and polyethylene (PP) converter foil; b) tracks of recoil protons after interaction of 2.5 MeV neutrons.*

To validate the system, known standard targets of polyethylene and alumina (Al_2O_3) will be used. The particle detected by GEMpix are observed as tracks in the gas volume: the study of their morphology end charge will provide a detailed study of the reaction products.

7 List of Conference Talks by LNF Authors in Year 2022

1. A. Tamburrino, Rivelatore Timepix3 per la misura dei prodotti di decadimento del radon, XXXVIII Congresso Nazionale Airp, Milano, 28–30 settembre 2022
2. L.Foggetta, The use of Timepix silicon detectors for detecting beam characteristics in different particle beam types and their daily use, 6th International Conference Frontiers in Diagnostic, Technologies, 19-21 October 2022
3. D. Pacella, Feasibility study for out-vessel GEM gas detectors for 1-D energy resolved X-ray imaging at ITER, 6th International Conference Frontiers in Diagnostic Technologies, 19-21 October 2022

8 Publications

List of papers published by Frascati n_TOF members in 2022:

1. A. Tamburrino, G. Claps, F. Cordella, F. Murtas, D. Pacella, Timepix3 detector for measuring radon decay products, Journal of Instrumentation, 2022, 17(6), P06009
2. G. Pucella et al., Overview of the FTU results, Nuclear Fusion, 2022, 62(4), 042004

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1 . A. Feruglio, Degree Thesis on ”Misura della Concentrazione e della Distribuzione del ^{10}B per la Boron Neutron Capture Therapy con Rivelatori Timepix”, Pisa University (2022)

2 . X. Llopart et al., Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements. Nucl. Instr. Meth. A 581, 485 (2007)

3 . L. Cosentino, F. Murtas et al., Proposal to the ISOLDE and Neutron Time-of-Flight Committee, Measurement of (n,cp) reactions in EAR1 and EAR2 for characterization and validation of new detection systems and techniques, CERN-INTC-2022-019/INTC-P-629 (2022)

4 . G. Claps, F. Murtas, L. Foggetta, C. Di Giulio, J. Alozy and G. Cavoto, Diamondpix: A CVD diamond detector with timepix3 chip interface,IEEE Trans. Nucl. Sci. 65 (2018) 2743

5 . T. Poikela et al. 2014. Timepix3: a 65k channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout. J. Instrum. 9, C05013 (2014)

6 . F. Murtas, The GEMPix detector, Rad. Meas. 138, 106421 (2020)