n_TOF: TIMEPIX-BASED DIAGNOSTIC SYSTEMS FOR NEUTRONS DETECTION, CROSS SECTION MEASUREMENTS AND BNCT

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1 Introduction

Our activity during the last year falls in the framework of a collaboration between ENEA and INFN in Frascati and follows two main research lines: the development of a new diagnostic system based on GEMpix and Timepix detectors [1] for neutron cross section measurements and the characterization of new timepix-based detectors for neutrons and charged particles detection [2; 3]. These activities found physical interest in the field of nuclear fusion, radiation protection, medical applications, and nuclear astrophysics, as will be explained in the following sections. After a brief introduction to the n_TOF facility and the main neutron sources used by our group, the report will focus on the main results obtained in the last year: the characterization of the Side-On GEMpix on the FNG facility and the preliminary results obtained on the *n_TOF* facility. Paragraph 4 will be dedicated to a brief overview of Timepix3 QUAD measurements on the *n_TOF* facility and on the LENA reactor for the Boron Neutron Capture Therapy (BNCT). The last paragraph will briefly resume the status of the activities on the computational resources of *n_TOF* collaboration.

2 Neutron Facilities

In the framework of the n_TOF collaboration, our group actively participates as both a support and a 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 traveling along a flight path of 185 m with a high instantaneous flux. In EAR1, the time-of-flight technique allows the measuring of neutron energy over a wide range with good resolution. At 12 m from the EAR1 station, there is the beam dump area, which is often used to test new detectors. In the second measuring station, called EAR2, the beam arrives after a trajectory of 20 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. Other 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 a moderated sealed neutron source of AmBe. The source of AmBe has been incorporated in a polyethylene structure 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 localized 50 cm from the AmBe source with a neutron flux of 763 n/cm^2/s. BNCT activity, instead, is carried out on the TRIGA MARK II fission reactor at the L.E.N.A. laboratory in Pavia. Important characterization tests of the new developed detector have been performed on the DAFNE Beam-Test Facility (BTF), especially their time and charge response. The BTF can provide electron and positron beams with a maximum energy of 500 MeV in bunches that can have until to 10^9 particles and a width from 1.5 to 40 ns. Then this beam revealed particularly useful to test experimental conditions for pulsed source at high intensity.

3 Measurements of low energy charged products with GEMpix detectors

In the framework of the n-TOF collaboration, the activity proposed by the ENEA/LNF group is in the field of nuclear fusion and focuses on the effects of radiation damage to structural materials constituting the inner part of Tokamaks, especially in the blanket and divertor which are subjected to extremely high neutron fluxes. Reactions of particular importance are (n, cp) reactions, which produce light charged particles such as protons, deuterons, tritons, and alpha particles, and are responsible for the generation 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 [4]. The study of neutron cross sections for some materials has important implications in other fields such as nuclear astrophysics and medical physics. (n, cp) reactions characterize many processes that take place inside stars. Among the most important reactions we mention those that produce protons for the subsequent ^{14}N(n, p)^{14}C reaction useful for helium-shell burning [5] and reactions producing ^{7}Li. In this second case, there is a discrepancy between models and measured data, and it is necessary to study also the (n, α) e (n, p) channels [6]. In nuclear medicine, there are also implications in several fields such as dosimetry, neutron therapy, and isotope production. A specific application in this field is summarized in paragraph 4. Within this research program, the work of the ENEA/LNF group focused on the realization of a new GEMpix detector [7] in a side-on geometry. The new side-on GEMpix has a standard configuration in its amplification and read-out (a triple GEM camera read by a Timepix1 quad [8]), but with a higher drift region (12 mm) and two side windows (fig. 1a).

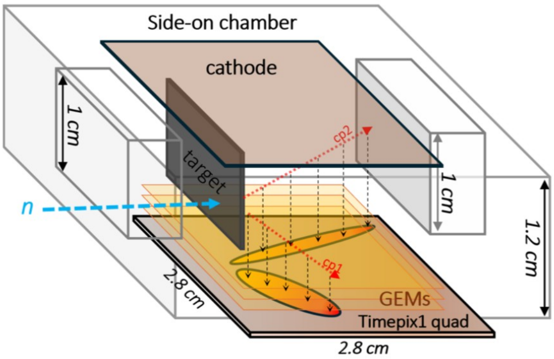
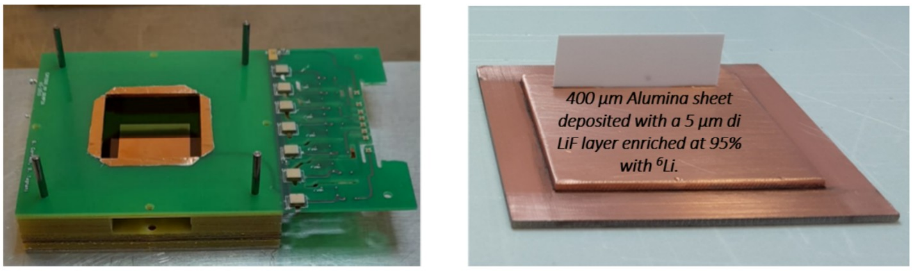


Figure 1: *A layout of the new side-on GEMpix showing its main components, in particular the cathode with the vertical target that faces the active volume of 1.2 cm. The tracks produced by the charged particles after a neutron interaction project the released charge on the Timepix quad plane generating the characteristic clusters.*

To reduce the proton recoil background, side windows have been made of glass (SiO_2). In addition, the cathode is removable so that to be substituted with another one equipped with a vertical target on one side at the beginning of the active volume. In particular, for the experimental tests performed in the last year, the target was a 5 μm layer of Lithium Fluoride (LiF) enriched with ^{6}Li at 95% deposited on a 400 μm Alumina (Al_2O_3) sheet with an area of 10×30 mm (fig. 2).



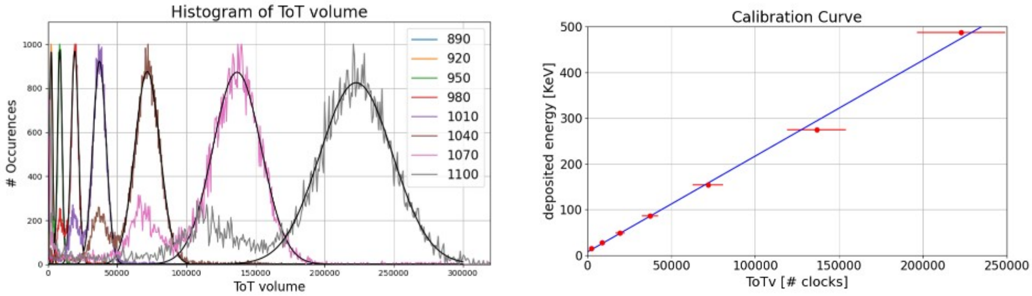
(a) (b)

Figure 2: *a) A photo of the new side-on GEMpix without cathode; b) photo of a copper cathode equipped with LiF deposited Alumina sheet.*

The experiment was aimed to study the capability of the new detector to identify and discriminate the triton and alpha products from the (n, ^{6}Li) reaction. Their measurement is particularly important in the fast neutron region where a significant background was expected.

3.1 Energy calibration and characterization tests on the HOTNES source

In order to estimate the energies of the charged particles under measurement, the first step was the energy calibration of the new detector. To simplify the procedure, calibration in energy has been realized with a ^{55}Fe source and performing a gain scan by setting different values to the voltage applied to GEMs (fig. 3a). To measure X-rays, the cathode was substituted with another one made of 15 μm aluminized mylar foil.



(a) (b)

Figure 3: *a) ToT volume histograms at increasing gain voltages with the relative gaussian fits; b) the calibration curve obtained by plotting the mean values of the gaussian versus deposited charge; error bars corresponds to the FWHM calculated from the gaussian fits.*

The calibration curve has been obtained by correlating the mean values of the ToT volume distributions and the deposited energies calculated with the applied gains. This was an important step because one point to investigate is the minimum energy at which the charged particles can be measured and discriminated.

After energy calibration, it was necessary to evaluate its correct operation, especially in presence of the target. Then, two cathodes have been prepared: one simple bare cathode and one with LiF deposited Alumina. With these two configurations, the new GEMpix has tested with thermal neutrons on the HOTNES source. As expected, when the LiF was inside, characteristic tracks due to alphas and tritons have been observed (fig. 4).

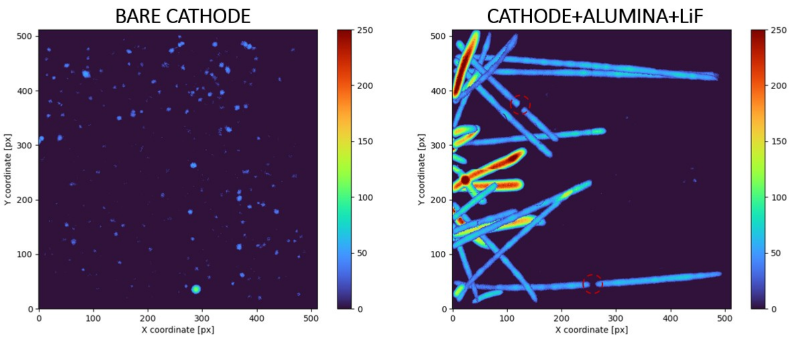
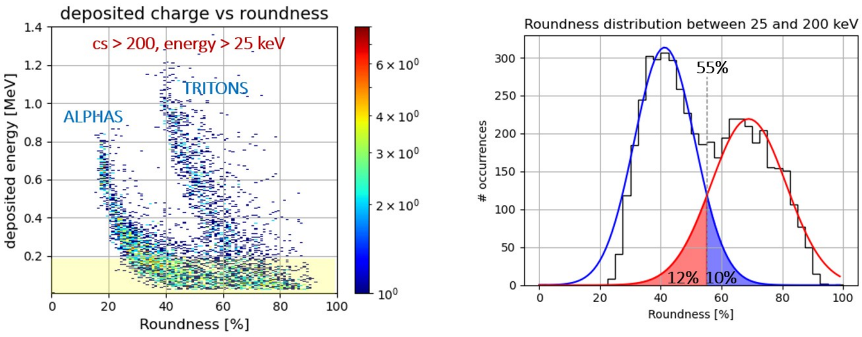


Figure 4: *Comparison of the images obtained on the HOTNES facility with a bare cathode and one equipped with LiF deposited Alumina sheet.*

Cluster analysis was carried out by defining a set of parameters such as: cluster size (cs, sum of the pixels constituting the cluster), ToT volume (ToTv, sum of all the ToT values of the cluster), Solidity (Sld, fraction between cluster size and convex hull containing the trace) and Roundness (Rnd, fraction between cluster size and the circumference area having a diameter equal to the distance of the most distant pixels in the cluster). By applying specific cuts to these parameters, it was possible to remove the residual contribution coming from gamma photons and highlight the two populations due to alpha and tritons as shown in fig. 5a.



(a) (b)

Figure 5: *a) 2D histogram of the deposited energy versus roundness showing the separation of alpha and triton population with a minimum energy of 0.2 MeV; b) roundness histogram of the observed particle in the energy range from 25 to 200 keV, showing the amount of overlapping between alpha and triton populations.*

As can be observed, the two populations are clearly separated for energies higher than 0.2 MeV while, at lower values, there is an overlapping that has been estimated at about 10%. More details on the detector characterization on the HOTNES source can be found on the proceedings of the 2025 International Conference on Applied Electronics as specified in the publications section of this report.

3.2 Preliminary results obtained on the *n_TOF* facility

Experimental tests with the side-on GEMpix on the n_TOF facility have been performed between the end of March and the beginning of February 2025. The main goal of the experiment was the testing of the discrimination capability of the side-on GEMpix on the alpha and triton particles produced by neutron interaction with ^{6}Li at different neutron energies, and estimate the amount of background respect to these charged products from ^{6}Li, especially in the higher energy range. For the tests, three types of cathodes have been substituted: a bare cathode, one with Alumina and one with LiF deposited Alumina. The first measurement was made with neutrons in the thermal energy range where only the contribution of alphas and tritons is expected. Cluster analysis has been further detailed by introducing additional cluster parameters: ToT mean (ToT value calculated as the average pixel ToT intensity within the cluster), eccentricity (eccentricity of the ellipse that has the same second moments as the region), minor axis and major axis (the lengths of the minor and major axes of the ellipse that has the same normalized second central moments as the region). A 2D histogram of the ToT mean versus the major axis clearly shows the presence of the two populations due to alpha and tritons coming from thermal neutron interactions (fig. 6).

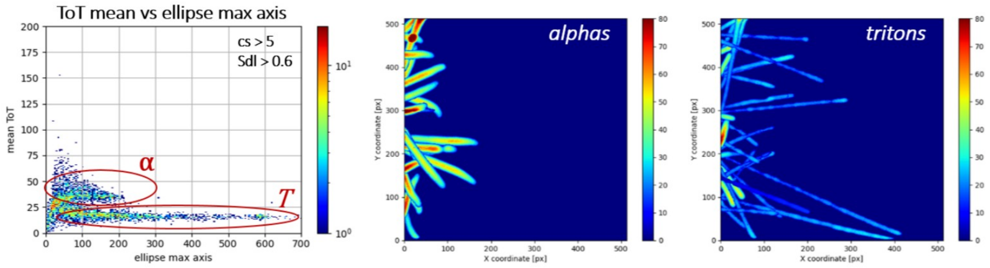


Figure 6: *a) 2D histogram in the ToT mean vs major axis with cuts on cs and Sdl, and images of the measured tracks from the alpha and triton populations.*

As shown in fig. 6a, the only cuts applied are on cs and Sdl, but it has been observed that a more accurate discrimination analysis, especially in higher neutron energy range, can be obtained by setting additional cuts on roundness, the minimum X coordinate (X_{min}, on the side facing the target) and the major axis. After the application of these additional cuts, a comparison of the measurements obtained with the cathode with Alumina and the one with LiF deposited Alumina have been performed for three neutron energy ranges and results are summarized in fig. 7.

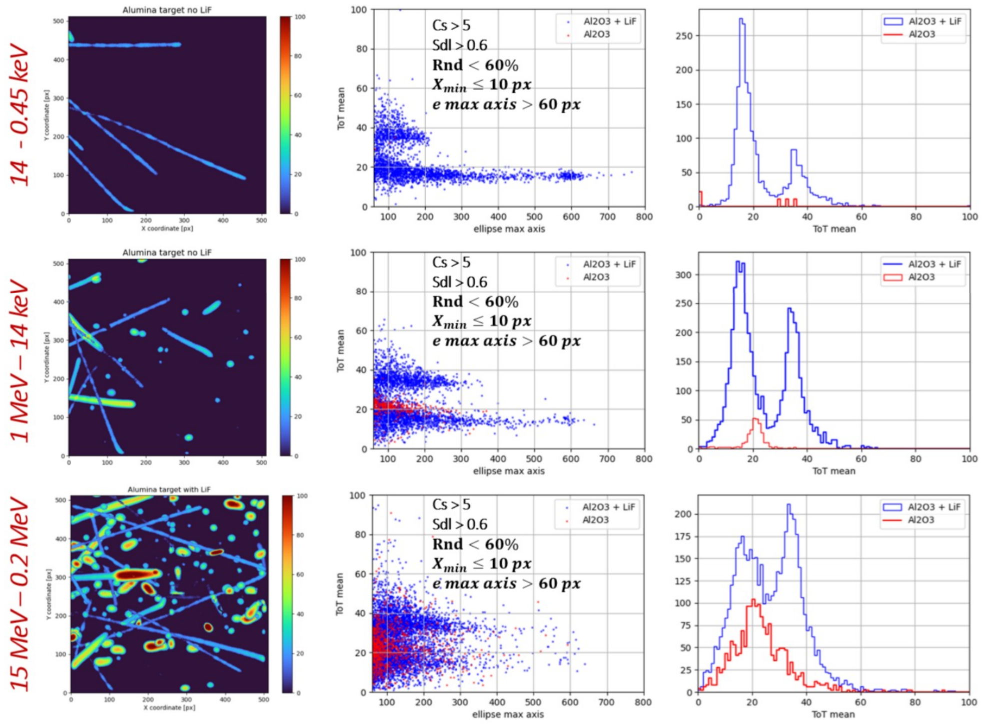


Figure 7: *2D images of the observed tracks during acquisitions for the three investigated neutron energy ranges, and the 2D histograms (ToT mean versus major axis) and ToT mean histograms with the LiF sample (blue) and not (red). The cuts applied on the cluster parameters are also referred in the legend of the central plots.*

As can be observed, the estimated background contribution increases with the neutron energies. It is practically zero for low energy neutrons, while its contribution increases at higher energies and has been estimated of about 3% for the 14 keV - 1 MeV range and about 30% for the 0.2 - 15 MeV range. In this last case, fluka MC simulations demonstrated that a significant part of the background comes from neutron interactions on the material constituting the detector chamber. It has been evaluated that a consistent background due to alpha and protons comes from the Alumina substrate where, in particular, some reactions takes place with Oxygen (^{16}O(n, α)^{13}C and ^{16}O(n, p)^{16}N) and Aluminum (^{27}Al(n, p)^{27}Mg and ^{27}Al(n, n+p)^{26}Mg). Then a very intense source of background due to protons comes from the recoil reactions from hydrogenated materials like the kapton of GEM foils and the epoxy case. These simulation studies are crucial to optimize the realization of the new prototype to further reduce the background and improve its discrimination capability. The new GEMpix chamber will have a new geometry and will be read by a Timepix4 chip [9]. At the moment, the new readout board that will host the Timepix4 chip has been realized (fig. 8) with a design that is compatible with the actual GEMpix chamber so that to test it with the old configuration.

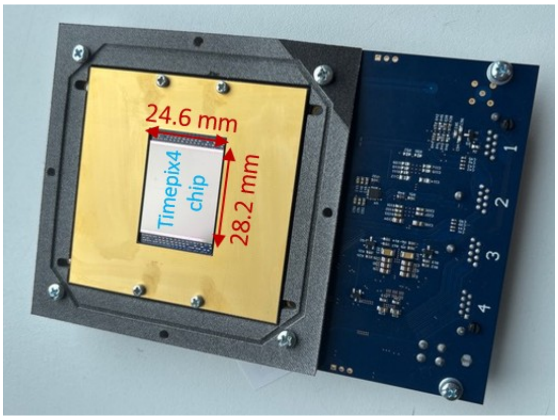


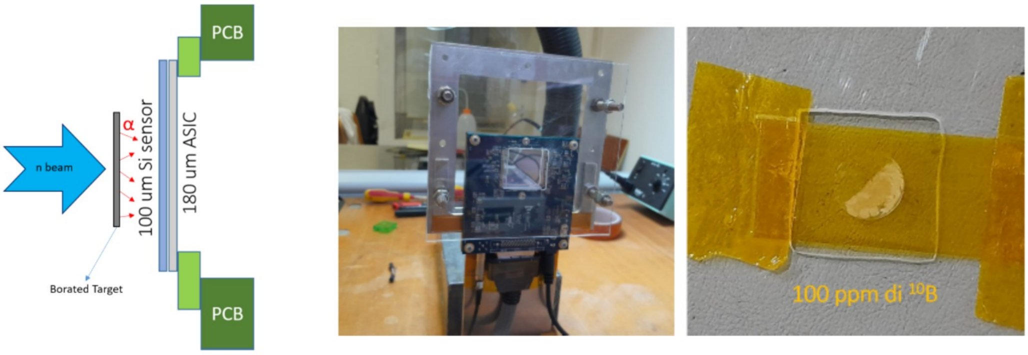
Figure 8: *Photos of the new readout board with a Timepix4 chip for the future GEMpix prototype.*

Among the advantaged offered by the new chip, Timepix4 can work in charge and time simultaneously, has a packed-based acquisition, a time resolution of 200 ps and a bandwidth of 20.48 Gbps. Timepix4 readout will allow a 3D track reconstruction and this will also improve significantly tracks discrimination.

4 Measurements of charged products with Timepix3 Quad

The diagnostic system for the n_TOF proposal also includes a solid state detector for the measurements of the higher energy reaction products ($> 2MeV$). In this range, a Silicon Timepix3 quad detector with a thickness of 500 μm has been proposed. It covers an area of 28×28 mm^2 with a matrix of 512×512 square pixels, having a pitch of 55 μm. It can acquire in three different modes with respect to the incident particles: counting, charge (ToT mode), or time of arrival (ToA). Timepix3 quad has been tested in the n_TOF EAR2 by using the 400 nm thick LiF sample enriched at 95 % with ^{6}Li (100 μg/cm^{2}) deposited on a 1.6 μm mylar foil and in the n_TOF EAR1 with a target of 400 μm graphite sheet placed at about 1 mm from the detector surface. Measurements in EAR2 have been analyzed and the main results shown in the previous report, while measurements in EAR1, acquired in 2025, are under analysis.

In the field of Boron Neutron Capture Therapy (BNCT), knowledge of the ^{10}B content in biological samples is of fundamental importance because it is correlated with the effectiveness of the treatment. In particular, it is important to evaluate the ^{10}B concentration and its spatial distribution inside cancerous tissues. Usually, two methods are used: the α Spectrometry [10] to measure the concentration and Neutron Auto-radiography [11] to image its spatial distribution. However, these two techniques must be applied separately, while auto-radiography is laborious and involves the destruction of the analyzed sample. Recently, a Silicon Timepix3 quad detector has been proposed because it is able to perform simultaneously the α Spectrometry required to measure the concentration of ^{10}B and imaging of the spatial distribution of this concentration. The used Timepix3 quad was like the one presented previously but having a silicon active layer with a thickness of 100 μm and no underlying PCB board. The experimental setup included a PVC mask with a window at the center for inserting the sample, as shown in fig.9.



(a) (b)

Figure 9: *a) The layout of the experimental set-up with the new TPX3 quad detector, there is no PCB board on back of the quad; b) a photos of the diagnostic set-up with and of the pvc mask with the attached sample inside.*

Experiment carried out in 2024 aimed to realize the Boron imaging concentration on biological samples with known concentrations: they were some shredded liver tissues with a concentration of 50 and 100 ppm deposited on 100 μm mylar supports.

These samples were placed on the hole of the pvc mask at a distance of about 1 mm from the Timepix3 quad surface. Then they were irradiated by a neutron beam with a diameter of 5 cm. The LENA reactor provides a thermal neutron energy spectrum peaked at 25 mV and was operated at maximum possible power (250 kW) in order to change the neutron flux. The estimated neutron flux on the sample is about 6.2×10^{6} neutrons/cm$^{2}\cdot$s. TPX3 quad acquires not only the α particles produced by the reaction ^{10}B(n,α)^{7}Li but also the background due especially to the gamma activation of the surrounding materials. Then a track discrimination analysis has been performed in order to identify the alpha tracks and realize the corresponding image of ^{10}B deposition (fig.9). The image obtained with the cumulative of the centroids of the tracks in the alpha region shows clearly the area covered by the biological samples, in particular those having a concentration of 50 ppm in ^{10}B (fig 10).

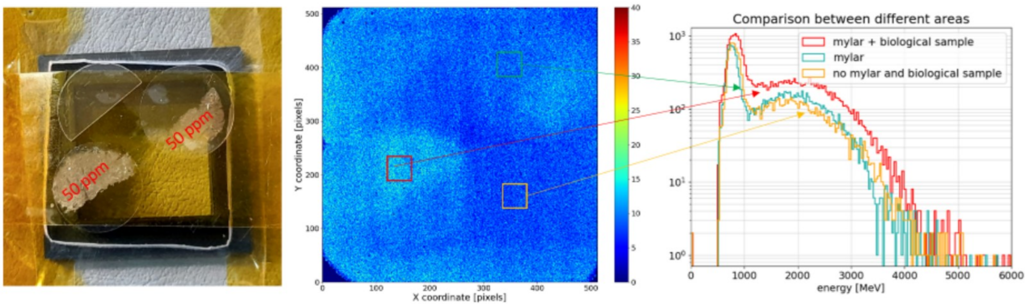


Figure 10: *A photo of the samples mounter on the support mask and the 2D image obtained with centroid of the alpha tracks, on the right the histogram of the three selected areas that shows the contribution of the biological sample doped with* ^{10}B *at a concentration of 50 ppm.*

As can be observed in fig. 10, the centroid image highlights the areas where biological sample is present providing an image distribution of the ^{10}B at 50 ppm in concentration, the lower tested value. In addition, the ToT volume distributions in three different areas shows clearly the contribution of the sample respect to the background, in particular, the difference respect to the mylar area provides a measure of concentration. Further details can be found in the master's thesis of A. Tamburrino [12] and in the paper listed in the publications section of this report.

5 Support to calculation activities and computational resources

The Italian n_TOF collaboration owns dedicated computational resources at Cloud@CNAF, the main data processing and computing technology research center of the INFN. The computational resources consist in 600 HS06, which are roughly 4 CPU made of 16 cores. These are deployed using 4 virtual machines, sharing a single temporary storage volume as provisional disk to run simulations. The most of the calculation activities relies on the utilization of the Geant4 Monte Carlo code. At the moment, no scheduler is installed on the virtual machines (e.g. slurm), and the operative system is based on AlmaLinux 9.2. 10TB of storage are allocated at Tier1, and they are accessible through the WebDAV protocol and the IAM authentication.
The n_TOF group of Frascati is directly involved in the coordination of the activities requiring the computational resources inside the whole Italian collaboration. The use of the most advanced techniques in Software Development, such as the use of code versioning (i.e. git though the Baltig INFN service), and the proper access to the storage volume are promoted inside the n_TOF users community.

6 List of Conference Talks and Posters by LNF Authors in Year 2025

1. G. Claps, Side-on GEMpix detector for the measurement of charged particles from neutron induced reaction, 8–9 September 2024, Pilsen (Czech Republic)

7 Publications

List of papers published by Frascati n_TOF members in 2025:

1. V. Michalopoulou et al., Measurement of the 235U fission cross section relative to the standard 10B(n, α) reaction at the CERN n_TOF facility: Results for En ¡ 2 eV, Applied Radiation and Isotopes, Volume 226, December 2025, 112063, DOI: 10.1016/j.apradiso.2025.112063
2. A. Tamburrino, G. Claps, N. Protti, G. Romanelli, V. De Leo, F. Cordella, D. Pacella, S. Altieri, F. Murtas, Timepix3-based detector: a novel approach for evaluating 10B concentration and spatial distribution in boron neutron capture therapy, Eur. Phys. J. Plus (2025), DOI: 10.1140/epjp/s13360-025-06860-6
3. C. Domingo-Pardo et al., Neutron capture measurements for s-process nucleosynthesis, European Physical Journal A, Open source preview, 2025, 61(5), 105, DOI: 10.1140/epja/s10050-025-01563-z
4. G. Claps, A. Tamburrino, V. De Leo, F. Cordella, D. Pacella, A. Pietropaolo, A. Zerbini, M. A. Vincenti, Side-on GEMpix detector for the measurement of charged particles from neutron induced reactions, 2025 International Conference on Applied Electronics (AE), DOI: 10.1109/AE66163.2025.11197842

References

1 . 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)

2 . 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

3 . A. Tamburrino, PhD Thesis on "Characterization of a new pixelated diamond detector for fast neutron diagnostics on fusion reactors", Sapienza University of Rome (2024)

4 . 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)

5 . Falk Herwig 2005, Annual Review of Astronomy & Astrophysics, vol. 43, Issue 1, pp.435-479

6 . Barbagallo et al., (n,cp) reactions study at the n_TOF facility at CERN: results for the Cosmological Lithium problem, CERN Proc. 1 (2019) pp.259-264

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

8 . 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)

9 . X. Llopart et al., Timepix4, a large area pixel detector readout chip which can be tiled on 4 sides providing sub-200 ps timestamp binning, Journal of Instrumentation, Volume 17, January 2022

10 . S. Bortolussi e S. Altieri. "Boron concentration measurement in biological tissues by charged particle spectrometry". In: Radiation and Environmental Biophysics 52 (4 2013). DOI: 10.1007/s00411-013-0480-y

11 . S. Altieri et al. "Neutron autoradiography imaging of selective boron uptake in human metastatic tumors". In: Applied Radiation and Isotopes 66 (12 2008). DOI: 10.1016/j.apradiso.2008.05.007

12 . A. Tamburrino, Master's thesis on "Boron Neutron Capture Therapy: valutazione della distribuzione spaziale e della concentrazione di ^{10}B mediante il rivelatore Quad Timepix3", Università degli studi di Roma Tor Vergata (2024)