**(n_TOF Collaboration) Patronis, N.; Mengoni, A.; Goula, S.; Aberle, O.; Alcayne, V.; Altieri, S.; Amaducci, S.; Andrzejewski, J.; Babiano-Suarez, V.; Bacak, M.; ...**

Patronis et al. *EPJ Techniques and Instrumentation* ( 2023) 10:13
https://doi.org/10.1140/epjti/s40485-023-00100-w

EPJ Techniques and Instrumentation

RESEARCH ARTICLE Open Access

# Status report of the n_TOF facility after the 2nd CERN long shutdown period

N. Patronis[1,2*], A. Mengoni[3,4], S. Goula[1], O. Aberle[2], V. Alcayne[5], S. Altieri[6,7], S. Amaducci[8], J. Andrzejewski[9], V. Babiano-Suarez[10], M. Bacak[2], J. Balibrea Correa[10], C. Beltrami[6], S. Bennett[11], A.P. Bernardes[2], E. Berthoumieux[12], R. Beyer[13], M. Boromiza[14], D. Bosnar[15], M. Caamaño[16], F. Calviño[17], M. Calviani[2], D. Cano-Ott[5], A. Casanovas[17], D.M. Castelluccio[3,4], F. Cerutti[2], G. Cescutti[18,19], S. Chasapoglou[20], E. Chiaveri[2,11], P. Colombetti[21,22], N. Colonna[23], P. Console Camprini[4,3], G. Cortés[17], M.A. Cortés-Giraldo[24], L. Cosentino[8], S. Cristallo[25,26], S. Dellmann[27], M. Di Castro[2], S. Di Maria[28], M. Diakaki[20], M. Dietz[29], C. Domingo-Pardo[10], R. Dressler[30], E. Dupont[12], I. Durán[16], Z. Eleme[1], S. Fargier[2], B. Fernández[24], B. Fernández-Domínguez[16], P. Finocchiaro[8], S. Fiore[3,31], F. García-Infantes[32,2], A. Gawlik-Ramiega[9], G. Gervino[21,22], S. Gilardoni[2], E. González-Romero[5], C. Guerrero[24], F. Gunsing[12], C. Gustavino[31], J. Heyse[33], W. Hillman[11], D.G. Jenkins[34], E. Jericha[35], A. Junghans[13], Y. Kadi[2], K. Kaperoni[20], G. Kaur[12], A. Kimura[36], I. Knapová[37], M. Kokkoris[20], M. Krtička[37], N. Kyritsis[20], I. Ladarescu[10], C. Lederer-Woods[38], J. Lerendegui-Marco[10], G. Lerner[2], A. Manna[4,39], T. Martínez[5], A. Masi[3], C. Massimi[4,39], P. Mastinu[40], M. Mastromarco[23,41], E.A. Maugeri[30], A. Mazzone[23,42], E. Mendoza[5], V. Michalopoulou[20], P.M. Milazzo[18], R. Mucciola[25,43], F. Murtas[44ˆ], E. Musacchio-Gonzalez[40], A. Musumarra[45,46], A. Negret[14], A. Pérez de Rada[5], P. Pérez-Maroto[24], J.A. Pavón-Rodríguez[24,2], M.G. Pellegriti[45], J. Perkowski[9], C. Petrone[14], E. Pirovano[29], J. Plaza del Olmo[5], S. Pomp[47], I. Porras[32], J. Praena[32], J.M. Quesada[24], R. Reifarth[27], D. Rochman[30], Y. Romanets[28], C. Rubbia[2], A. Sánchez-Caballero[5], M. Sabaté-Gilarte[2], P. Schillebeeckx[33], D. Schumann[30], A. Sekhar[11], A.G. Smith[11], N.V. Sosnin[38], M.E. Stamati[1,2], A. Sturniolo[21], G. Tagliente[23], A. Tarifeño-Saldivia[17], D. Tarrío[47], P. Torres-Sánchez[32], E. Vagena[1], S. Valenta[37], V. Variale[23], P. Vaz[28], G. Vecchio[8], D. Vescovi[27], V. Vlachoudis[2], R. Vlastou[20], A. Wallner[13], P.J. Woods[38], R. Zarrella[4,39] and P. Zugec[15]

*Correspondence:
nikolaos.patronis@cern.ch
[1]University of Ioannina, Ioannina, Greece
[2]European Organization for Nuclear Research (CERN), Geneva, Switzerland
Full list of author information is available at the end of the article
ˆDeceased

**Abstract**

During the second long shutdown period of the CERN accelerator complex (LS2, 2019-2021), several upgrade activities took place at the n_TOF facility. The most important have been the replacement of the spallation target with a next generation nitrogen-cooled lead target. Additionally, a new experimental area, at a very short distance from the target assembly (the NEAR Station) was established. In this paper, the core commissioning actions of the new installations are described. The improvement in the n_TOF infrastructure was accompanied by several detector development projects. All these upgrade actions are discussed, focusing mostly on the future perspectives of the n_TOF facility. Furthermore, some indicative current and future measurements are briefly reported.

**Keywords:** Neutron time of flight; Spallation target; Nuclear astrophysics; Neutron physics; Neutron induced fission; Neutron reactions

## 1 Introduction

The neutron time-of-flight (n_TOF) facility is based on a proposal by Carlo Rubbia [23] of establishing a high intensity neutron source at CERN, by taking advantage of the specific characteristics of the on-site accelerator complex. The facility became operational in 2001. The main motivation for the construction of this neutron time-of-flight facility was the production of high accuracy nuclear data for innovation in energy applications [24] and nuclear astrophysics studies [11].

One of the principal activities taking place at n_TOF is that of obtaining nuclear data relevant for the development of innovative systems for energy production and nuclear waste transmutation through accelerator-driven systems (ADS) and Generation IV fast reactors [3]. High accuracy, high precision and high-resolution cross section data are needed, in a wide energy range, for a variety of major and minor actinides [12], as well as for coolant, spallation and structural materials [18]. A second major branch of the scientific activity at n_TOF is oriented to the study of neutron induced reactions of astrophysical interest [11], in particular those relevant for understanding the nucleosynthesis of heavy elements in stellar environments. Finally, at n_TOF, several reaction studies of interest for medical applications have been performed in the past (e.g. [22]) and many more are considered for investigation in the near future.

Since its first year of operation and up to 2018, the n_TOF facility went through different phases of operation and significant upgrades. During the 2nd long shutdown period of the CERN accelerator complex (LS2), several actions to extend the capabilities of the facility were accomplished.

A brief description of the n_TOF facility is given in the next section. In the following two sections the recently performed upgrade activities will be described along with the corresponding commissioning actions. Finally, in the last section, the improvements with respect to the experimental conditions are discussed along with the perspectives of the n_TOF facility.

## 2 The n_TOF facility

The n_TOF facility is located at the European Organization for Nuclear Research (CERN). The neutron production is based on spallation reactions induced by 20 GeV proton pulses delivered by the CERN Proton Synchrotron (PS) accelerator. The pulsed proton beam is directed through the FTN beam line towards the n_TOF nitrogen-cooled lead target. Each proton pulse has a nominal intensity of $8.5 \times 10^{12}$ protons. For each proton impinging on the lead target, approximately 300 neutrons are produced through spallation reaction mechanisms. The maximum repetition rate of the delivered proton pulses is 0.8 Hz while the time width of each pulse is 7 ns (rms) allowing for excellent energy resolution of the produced neutron beam, even for the GeV neutron energy region.

Figure 1 shows a layout of the facility with the two experimental areas devoted to TOF measurements. The first experimental area (EAR1), located at the end of a horizontal 185 m long flight path, was commissioned in 2001 and is used for measurements requiring very high neutron energy resolution. The vertical beam line leading to the second experimental area (EAR2) has a much shorter flight path of 19 m. The commissioning of EAR2 took place in 2014. In this experimental area, thanks to its high neutron flux, measurements on small and/or radioactive samples are feasible, even when the mass of the sample is just a few mg. In both experimental areas, charged particles are removed from the beam

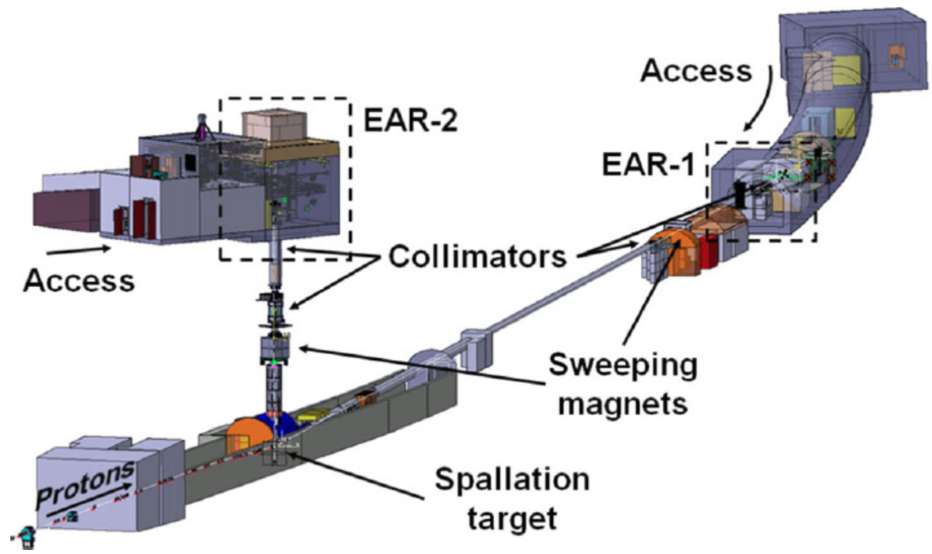


**Figure 1** The layout of the n_TOF facility at CERN related to EAR1 and EAR2. The direction of the proton beam, the lead spallation target and the main components of the two TOF beam lines are presented

**Table 1** Main characteristics of the experimental areas of the n_TOF facility

| | EAR1 | EAR2 |
|---|---|---|
| Energy range | 10 meV–1 GeV | 10 meV–100 MeV |
| Energy resolution | $10^{-4}$–$10^{-2}$ | $10^{-3}$–$10^{-2}$ |
| The two options of neutron beam collimator ⌀ (cm) | 1.8/8.0 | 3.0/6.7 |
| Neutrons/pulse for each neutron beam collimation option | $5.5 \cdot 10^5/1.2 \cdot 10^7$ | $2.2 \cdot 10^7/2.0 \cdot 10^8$ |

by “sweeping magnets”, while the beam aperture is defined through collimators and additional shielding elements. The final diameter of the beams, in both experimental areas, is defined by a shaping, downstream collimator, located just before the experimental area. Two options of beam apertures are available for each area, while the beam optical elements allow for a well defined and sharp spatial profile of the neutron beams for optimal low background conditions. The main characteristics of the two experimental areas of the n_TOF facility are summarized in Table 1.

To take full advantage of the excellent time (i.e. energy resolution) characteristics of the neutron pulsed beam, high rate digitisation of the detectors analog signals is performed. The n_TOF data acquisition system (DAQ) is based on SP Devices (digitizers), which offer high sampling rates in the 14–1800 MHz range, a resolution between 8 and 14 bits and a total per-trigger-acquisition-time up to 100 ms. The trigger signal for the n_TOF DAQ comes from the beam current transformer (BCT), from the PS accelerator and corresponds to the arrival of a proton pulse that is directed to the n_TOF spallation target. Following the trigger signal, the digitizers record the full waveform of the recorded pulses according to the adopted sampling rate. More details on the n_TOF DAQ system can be found in the [1].

Within the scientific program of the n_TOF Collaboration, a great variety of neutron reaction studies takes place. Depending on the physics case dedicated experimental setups are available. Throughout the more than twenty years of operation, the accumulated experience of the n_TOF research teams led to improvements and upgrades of existing experimental setups as well as to the development of new advanced detection systems. An overview of the latest advances on neutron capture measurements can be found in [15], while an overview of the fission setups is provided by [12]. For neutron induced reactions where one or more of the reaction products is a light charged particle, specific instrumentation has been developed in the most recent years and has been successfully used (e.g. [14]) or is still under development and characterization (e.g. [10, 13]).

## 3 Upgrade actions during LS2 and afterwards

During LS2, several upgrade activities were realized at the n_TOF facility, leading to a successful transition into its 4th phase of operation. These upgrade activities can be categorized into two different groups: (i) the infrastructure upgrades that were mostly realized by CERN working groups, and (ii) major detector development projects, taken over by n_TOF Collaboration teams.

The most important upgrade action has been the replacement of the lead spallation target that served the facility for more than ten years. The new target, featuring sliced, nitrogen-cooled lead blocks is shown in Fig. 2. This design is aiming to sustain the excellent beam characteristics for EAR1 achieved with the previous target, while improving the neutron flux and energy resolution in EAR2. It has to be mentioned that the previous (2nd) lead spallation target was designed and fabricated much before the establishment of EAR2 in 2014. For this reason, the beam exit path towards to EAR2 was not optimized (no beam window, no specific moderator) and during the previous phase of n_TOF operation, the neutron beam energy distribution in EAR2 was suffering from quite pronounced oscillations caused by neutron absorption within the structural materials of the target. For the same reasons, the Monte Carlo calculations of the moderation length (related to the so called "resolution function") for the neutrons transported towards EAR2 showed a rather complicated structure. The extended dispersion of the moderation length imposed difficulties in the resonance analysis as well as in the TOF-to-energy conversion. All these previous issues were successfully addressed though the design of the 3rd generation spalla-

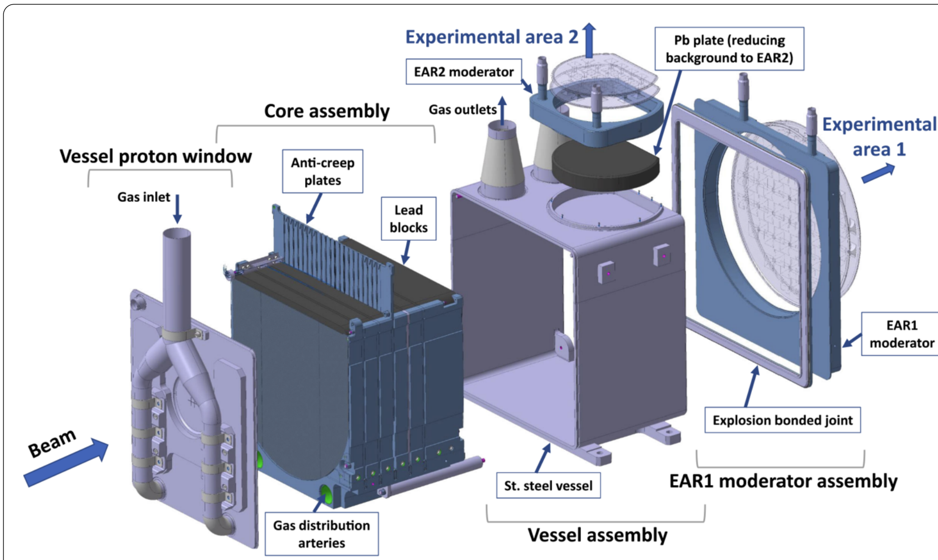


**Figure 2** Exploded model of the 3rd generation lead spallation target [16]

tion target. Indeed, Monte Carlo simulations showed that the neutron flux in EAR2 would be highly improved with respect to the previous one and at the same time the resolution function would be significantly simplified and better defined with obvious benefits to the quality of the experimental data. Preliminary commissioning experimental data fully confirm the Monte Carlo simulations. More details on the 3rd generation n_TOF spallation target can be found in the reference [16].

The second major n_TOF infrastructure development during LS2 was the establishment of a new experimental area located at about 3 m distance, on the side of the lead spallation target. This new experimental area, named NEAR Station [17, 20] (Fig. 3), offers much higher neutron flux than EAR1 and EAR2 and will be devoted mostly to irradiation and activation studies. The very high neutron flux is instrumental when limitations on the sample mass are imposed, as for instance when radioactive samples are considered. In the activation area of the NEAR Station, nuclear astrophysics measurements are foreseen after appropriate moderation and filtering of the neutron beam towards quasi-Maxwellian shaped energy distributions. The proof-of-principle of beam energy filtering using $B_4C$ filters is one of the running experiments of the n_TOF 2022-2023 campaigns [25]. Besides the NEAR Station activation area, an irradiation-specific area is also operational. In this sub-area, material irradiation hardness studies are taking place already since 2022. The samples are placed in specially designed air-tight containers which are then installed right next to the spallation target. Due to harsh radiation conditions, the samples handling is performed by a robot.

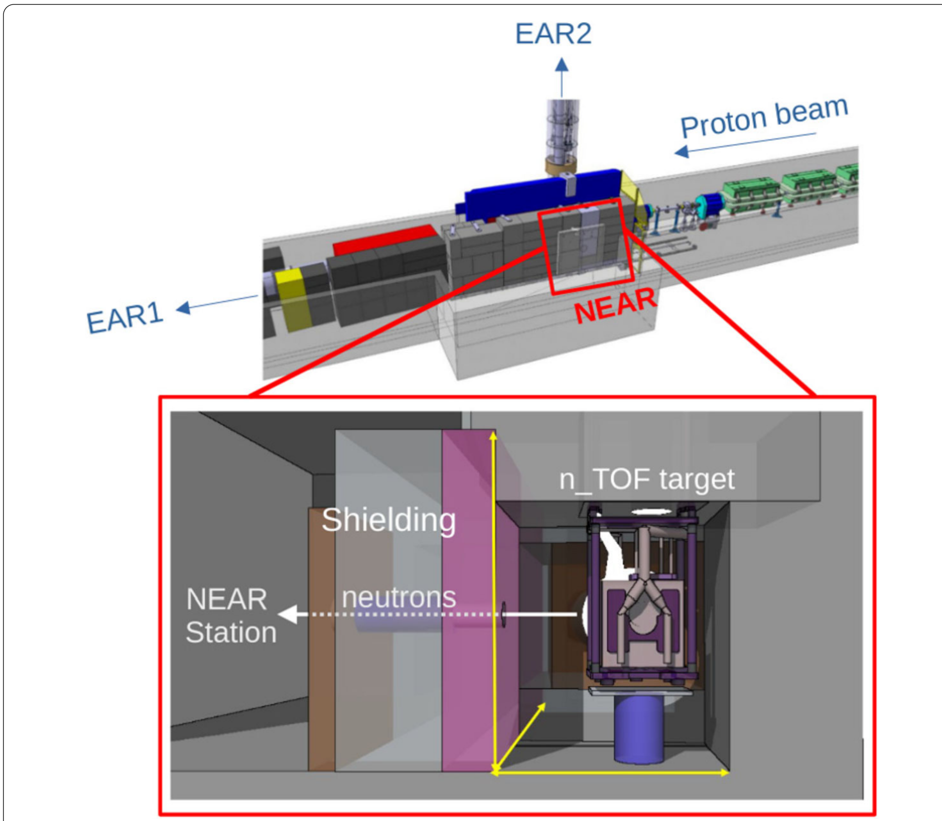


**Figure 3** The newly built 3rd n_TOF experimental area: The NEAR station

Apart from the aforementioned major upgrade actions, several additional significant developments of the n_TOF facility took place during LS2. For instance, the collimator system of EAR1 was replaced with a new one that allows for a much faster exchange between the available beam apertures. Furthermore, the EAR1 beam line sweeping electromagnet was replaced by a permanent magnet, enabling stable operation with zero energy consumption.

In addition to these upgrades devoted to improving the neutron beam characteristics, the n_TOF teams took advantage of the LS2 period to develop, characterize and deliver innovative detection setups that provide the ability to perform new series of measurements and to investigate previously unexplored physics cases. One of those developments is the i-TED setup [4]. i-TED is a $\gamma$-ray detection system based on the Compton imaging technique. In this way, the emitted $\gamma$-rays from capture events within the sample volume can be identified and selected. Accordingly, the signal to background ratio can be significantly enhanced allowing for measurement with minimal sample masses [5]. On the same direction, of performing neutron capture reaction studies with low mass and/or radioactive samples, the high instantaneous flux of EAR2 is instrumental. Even though the high instantaneous flux of EAR2, is in principle beneficial for neutron capture measurements, at the same time, causes high counting rates and strong pile-up events in the detection systems. These issues were solved through the implementation of small-volume segmented total-energy detectors (sTED) [2] arranged in a compact configuration around the capture sample [6]. The high segmentation of low volume detectors allowed for the shortening of the sample to detector distance resulting in better signal to background ratio, keeping at the same time the counting rates in well manageable levels.

Several other projects progressed and will be finalized within the coming months at n_TOF. These detection setups concern the study of neutron induced reactions, where one of the outgoing charged particles is a low mass charged particle: $(n,cp)$ reactions [10, 13]. These particle detection setups will enable the thorough experimental study of many $(n,cp)$ reactions that are either completely unexplored or the existing information is scarce and discrepant. Of course, this is a long-term research plan covering more than a decade of intense experimental and data analysis effort. Furthermore, the abilities of the n_TOF facility in the open research field of $(n,n')$ reaction studies by using in-beam $\gamma$ ray spectroscopy through specially designed HPGe detectors are being explored [7]. Moreover, improvements on the fission detector setups together with new developments (e.g. [8, 9]) are expected to be accomplished within the 2023 n_TOF campaign.

## 4 Commissioning activities after LS2

Given the important developments that took place during LS2, the neutron beams of both TOF experimental areas (EAR1 & EAR2) of the n_TOF facility have been commissioned thoroughly. For this purpose, different detection setups were utilized. The adopted setups were based on well characterized detector configurations and on well known reference reactions. In particular, concerning the determination of the energy dependance of the neutron flux, $^{235}$U$(n,f)$, $^{10}$B$(n,\alpha)$ and $^{6}$Li$(n,\alpha)$ where used as reference reactions by applying the setups that are listed in Table 2 and shown in Fig. 4 and Fig. 5. Besides the neutron beam flux, the beam spatial profile was determined by means of the position sensitive PPAC detectors and by $3 \times 3$ cm Timepix detectors.

For both TOF experimental areas (EAR1 and EAR2), the energy resolution was determined using different neutron capture reactions and $C_6D_6$ $\gamma$-ray detectors. The detection

**Table 2** Adopted experimental setups and methods for the commissioning of the 4th phase of the n_TOF facility

| Detector/function | EAR1 | EAR2 |
|---|---|---|
| Micromegas/flux | $^{235}$U$(n, f)$ | $^{235}$U$(n, f)$ |
| | $^{10}$B$(n, \alpha)$ | $^{10}$B$(n, \alpha)$ |
| PPAC/flux & beam profile | $^{235}$U$(n, f)$ | $^{235}$U$(n, f)$ |
| Silicon monitor | $^{6}$Li$(n, \alpha)$ | $^{6}$Li$(n, \alpha)$ |
| PTB fission chamber/flux | $^{235}$U$(n, f)$ | |
| C6D6/resolution function | $^{197}$Au$(n, \gamma)$, $^{nat}$Ir$(n, \gamma)$ | $^{197}$Au$(n, \gamma)$, $^{nat}$Ir$(n, \gamma)$, $^{235}$U$(n, \gamma)$ |
| | $^{nat}$Fe$(n, \gamma)$, $^{nat}$Si$(n, \gamma)$ | $^{nat}$Fe$(n, \gamma)$, $^{77}$Se$(n, \gamma)$ |
| Timepix | PE for $n, p$ conversion | PE for $n, p$ conversion |

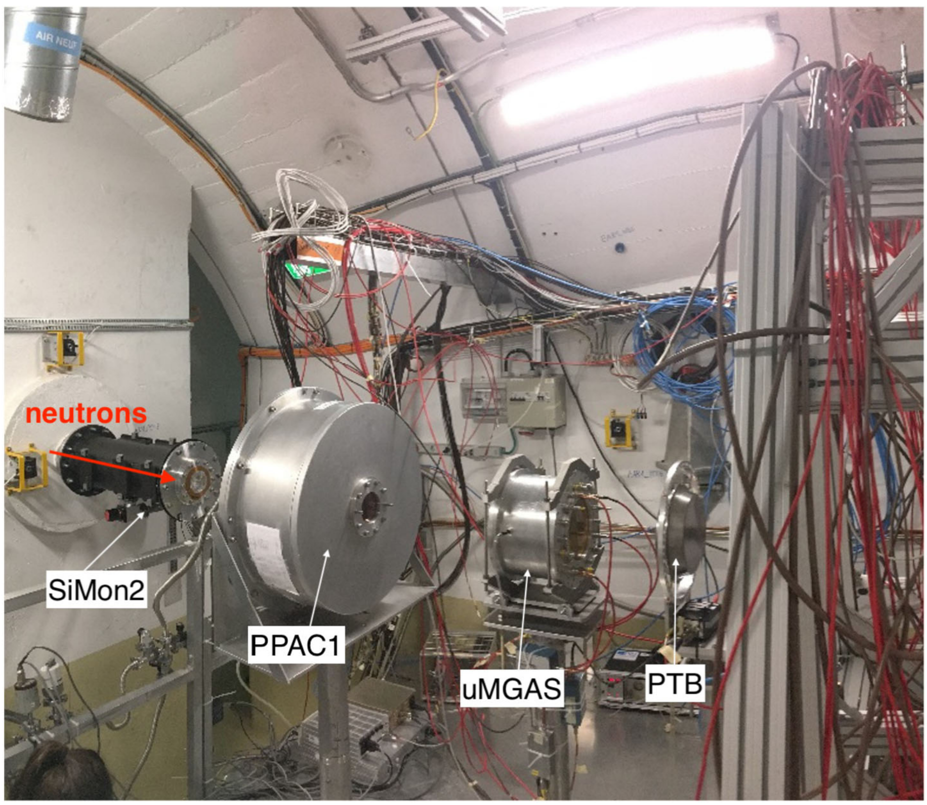


**Figure 4** The EAR1 flux measurement setup. The four detection setups can be seen

setups and the corresponding reference reactions that were used are summarized in Table 2. On this point, it has to be underlined that the neutron flux characterisation in both experimental areas is a demanding task considering that more than eleven orders of magnitude of neutron energies have to be covered. For this reason, in order to establish the best possible accuracy of the commissioning actions, the adoption of different experimental setups and reference reactions was instrumental.

The analysis of the commissioning data is on going (February 2022). Preliminary results show that, the neutron flux in EAR1 is at the same level with respect to the previous phase, while for EAR2 a significant increase in the neutron flux is observed along with a much smoother neutron energy distribution and improved resolution.

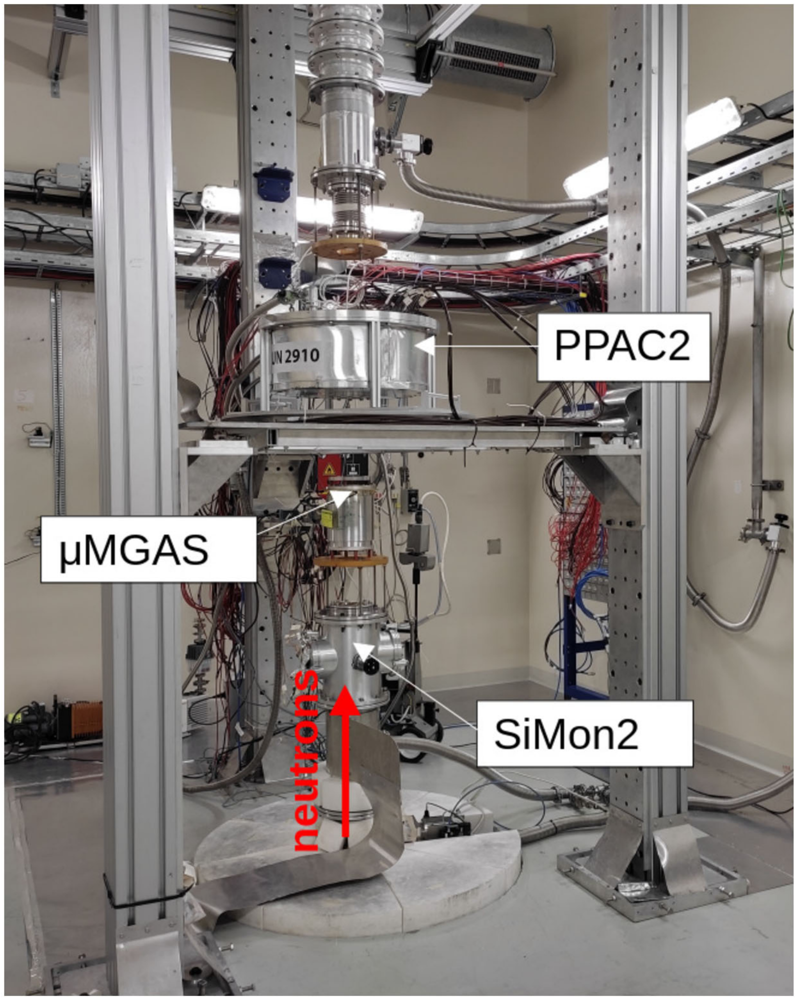


**Figure 5** The EAR2 flux measurement setup. The three detection setups can be seen

## 5 Conclusions and outlook

During the CERN Long Shutdown LS2 period, significant upgrade actions at the n_TOF facility were successfully accomplished, with the most important ones being the replacement of the lead spallation target and the establishment of a new experimental area, the NEAR station. These significant changes define the starting point of the 4th Phase of operation of the n_TOF facility.

During 2022, the Physics program of the n_TOF facility had a dynamic restart. The outcome of the first year of data-taking after LS2 was particularly fruitful. The long beam-on period, along with the establishment of a third experimental area, the NEAR Station, resulted in a wealth of experimental data taken at the facility. In particular, more than 20 scientific actions were accomplished during the 2022 n_TOF campaign concerning mostly neutron capture reaction studies for nuclear astrophysics purposes as well as for medical and nuclear technology applications. Thanks to the development of innovative detection setups during LS2, the experimental investigation of previously unexplored physics cases became feasible (e.g. measurement of the $^{79}$Se$(n,\gamma)$ reaction cross section) [19]. A significant part of the available beam time was devoted to further detector developments and tests that revealed the abilities of the n_TOF facility to launch new type of measurements in the near future.

For the current and future experimental campaigns, a quite ambitious physics program is already being followed, aiming mostly to nuclear astrophysics studies, fission reactions studies (e.g. measurement of $^{243}$Am($n,f$) reaction cross section [21]), detector development and proof-of-principle studies (e.g. [25], [13]).

**Acknowledgements**
In line with the principles that apply to scientific publishing and the CERN policy in matters of scientific publications, the n_TOF Collaboration recognises the work of V. Furman and Y. Kopatch (JINR, Russia), who have contributed to the experiment used to obtain the results described in this paper.

## Declarations

**Competing interests**
The authors declare that they have no competing interests.

**Author contributions**
All authors read and approved the final manuscript.

**Author details**
[1]University of Ioannina, Ioannina, Greece. [2]European Organization for Nuclear Research (CERN), Geneva, Switzerland. [3]Agenzia Nazionale per le Nuove Tecnologie (ENEA), Bologna, Italy. [4]Sezione di Bologna, Istituto Nazionale di Fisica Nucleare, Bologna, Italy. [5]Centro de Investigaciones Energeticas Medioambientales y Tecnologicas (CIEMAT), Madrid, Spain. [6]Sezione di Pavia, Istituto Nazionale di Fisica Nucleare, Pavia, Italy. [7]Department of Physics, University of Pavia, Pavia, Italy. [8]INFN Laboratori Nazionali del Sud, Catania, Italy. [9]University of Lodz, Lodz, Poland. [10]Instituto de Física Corpuscular, CSIC - Universidad de Valencia, Valencia, Spain. [11]University of Manchester, Manchester, United Kingdom. [12]CEA Irfu, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France. [13]Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany. [14]Horia Hulubei National Institute of Physics and Nuclear Engineering, Magurele, Romania. [15]Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia. [16]University of Santiago de Compostela, Santiago, Spain. [17]Universitat Politècnica de Catalunya, Barcelona, Spain. [18]Sezione di Trieste, Istituto Nazionale di Fisica Nucleare, Trieste, Italy. [19]Department of Physics, University of Trieste, Trieste, Italy. [20]National Technical University of Athens, Athens, Greece. [21]Sezione di Torino, Istituto Nazionale di Fisica Nucleare, Torino, Italy. [22]Department of Physics, University of Torino, Torino, Italy. [23]Sezione di Bari, Istituto Nazionale di Fisica Nucleare, Bari, Italy. [24]Universidad de Sevilla, Seville, Spain. [25]Sezione di Perugia, Istituto Nazionale di Fisica Nucleare, Perugia, Italy. [26]Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Teramo, Teramo, Italy. [27]Goethe University Frankfurt, Frankfurt, Germany. [28]Instituto Superior Técnico, Lisbon, Portugal. [29]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany. [30]Paul Scherrer Institut (PSI), Villigen, Switzerland. [31]Sezione di Roma, Istituto Nazionale di Fisica Nucleare, Roma, Italy. [32]University of Granada, Granada, Spain. [33]European Commission, Joint Research Centre (JRC), Geel, Belgium. [34]University of York, York, United Kingdom. [35]TU Wien, Atominstitut, Stadionallee 2, 1020 Wien, Austria. [36]Japan Atomic Energy Agency (JAEA), Tokai-Mura, Japan. [37]Charles University, Prague, Czech Republic. [38]School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom. [39]Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy. [40]INFN Laboratori Nazionali di Legnaro, Legnaro, Italy. [41]Dipartimento Interateneo di Fisica, Università Degli Studi di Bari, Bari, Italy. [42]Consiglio Nazionale Delle Ricerche, Bari, Italy. [43]Dipartimento di Fisica e Geologia, Università di Perugia, Perugia, Italy. [44]INFN Laboratori Nazionali di Frascati, Frascati (Roma), Italy. [45]Sezione di Catania, Istituto Nazionale di Fisica Nucleare, Catania, Italy. [46]Department of Physics and Astronomy, University of Catania, Catania, Italy. [47]Department of Physics and Astronomy, Uppsala University, Box 516, 75120 Uppsala, Sweden.

Received: 24 April 2023 Accepted: 8 May 2023 Published online: 17 May 2023

**References**

1. Abbondanno U, Aerts G, Alvarez F, Alvarez H, Andriamonje S, Andrzejewski J, Badurek G et al. (The n_TOF collaboration): the data acquisition system of the neutron time-of-flight facility n_TOF at cern. Nucl Instrum Methods Phys Res, Sect A, Accel Spectrom Detect Assoc Equip. 2005;538:692–702. https://doi.org/10.1016/j.nima.2004.09.002.
2. Alcayne VEA. 15th international conference on nuclear data for science and technology (ND2022). 2022. https://indico.frib.msu.edu/event/52/contributions/1094/.
3. Aliberti G, Palmiotti G, Salvatores M, Kim TK, Taiwo TA, Anitescu M, Kodeli I, Sartori E, Bosq JC, Tommasi J. Nuclear data sensitivity, uncertainty and target accuracy assessment for future nuclear systems. Ann Nucl Energy. 2006;33(8):700–33. https://doi.org/10.1016/j.anucene.2006.02.003.
4. Babiano V, Balibrea J, Caballero L, Calvo D, Ladarescu I, Lerendegui J, Mira Prats S, Domingo-Pardo C. First i-ted demonstrator: a compton imager with dynamic electronic collimation. Nucl Instrum Methods Phys Res, Sect A, Accel Spectrom Detect Assoc Equip. 2020;953:163228. https://doi.org/10.1016/j.nima.2019.163228.
5. Babiano-Suárez V, Lerendegui-Marco J, Balibrea-Correa J, Caballero L, Calvo D, Ladarescu I, Real D, Domingo-Pardo C, Calviño F, Casanovas A, Tarifeño-Saldivia A, Alcayne V, Guerrero C, Millán-Callado MA, Rodríguez-González T, Barbagallo M et al. Imaging neutron capture cross sections: i-ted proof-of-concept and future prospects based on machine-learning techniques. Eur Phys J A. 2021;57(6):197. https://doi.org/10.1140/epja/s10050-021-00507-7.

6. Balibrea-Correa J, Babiano-Suárez V, Lerendegui-Marco J, Domingo-Pardo C, Ladarescu I, Tarifeño-Saldivia A, Alcayne V, Cano-Ott D, González-Romero E, Martínez T, Mendoza E, Plaza J, Sánchez-Caballero A, Calviño F, Casanovas A, Guerrero C, Heinitz S, Köster U, Maugeri EA, Dressler R, Schumann D, Mönch I, Cristallo S, Lederer-Woods C, et al. 2023. First measurement of the 94Nb($n,\gamma$) cross section at the CERN n_TOF facility. https://doi.org/10.48550/arXiv.2301.11199.
7. Barbagallo M, Diakaki M, Eleme Z, Kokkoris M, Michalopoulou V, Negret A, Patronis N, Petrone C, Stamatopoulos A, Tassan-Got L, Tsinganis A, Vlastou R. HPGe detector test at n_TOF: feasibility study for neutron inelastic scattering measurements. Technical report. CERN, Geneva; 2021. https://cds.cern.ch/record/2765698.
8. Bennett S, Smith A, Garrett K, Wright T, Sekhar A, Chiaveri E, Sosnin N, Patronis N, Diakaki M, Bacak M, Tassan-Got L, Manna A, Colonna N, Cristallo S, Mengon A. LOI: commissioning of a double frisch-grid bragg detector for fission measurements and determination of n-induced background at EAR1 and EAR2. Technical report. CERN, Geneva; 2021. https://cds.cern.ch/record/2782319.
9. Bennett S, Smith G, Gerrett K, Wright T, Sekhar A, Chiaveri E, Sosnin N, Patronis N, Diakaki M, Bacak M, Tessan-Got L, Manna A, Colonna N, Cristallo S, Mengoni A. INTC-I-236 letter of clarification: commissioning of a Double frisch-grid bragg detector for fission measurements and determination of *n*-induced background at EAR1 and EAR2. Technical report. CERN, Geneva; 2022. https://cds.cern.ch/record/2798900.
10. Beyer R, Dietz M, Junghans A, Nolte R, Pirovano E, Vaz P. Measurement of double-differential charged-particle emission cross sections at n_TOF in the neutron energy range from 20 MeV. to 200 MeV. Technical report. CERN, Geneva; 2020. https://cds.cern.ch/record/2731958.
11. Colonna N, Aberle O et al. The nuclear astrophysics program at n_TOF (cern). EPJ Web Conf. 2017;165:01014. https://doi.org/10.1051/epjconf/201716501014.
12. Colonna N, Tsinganis A, Vlastou R, Patronis N, Diakaki M, Amaducci S, Barbagallo M, Bennett S, Berthoumieux E, Bacak M, Cosentino G, Cristallo S, Finocchiaro P, Heyse J, Lewis D, Manna A, Massimi C, Mendoza E, Mirea M, Moens A, Nolte R, Pirovano E, Sabaté-Gilarte M, Sibbens G, Smith AG, Sosnin N, Stamatopoulos A, Tarrío D, Tassan-Got L, Vanleeuw D, Ventura A, Vescovi D, Wright T, Zugec P. The fission experimental programme at the CERN n_TOF facility: status and perspectives. Eur Phys J A. 2020;56(2):48. https://doi.org/10.1140/epja/s10050-020-00037-8.
13. Cosentino L, Murtas F, Amaducci S, Mastromarco M, Vecchio G, Finocchiaro P, Patronis N, Goula S, Massimi C, Mazzone A, Colonna N, Pomp S, Tarrio D. Measurement of ($n,cp$) reactions in EAR1 and EAR2 for characterization and validation of new detection systems and techniques. Technical report. CERN, Geneva; 2022. https://cds.cern.ch/record/2809189.
14. Cosentino L, Musumarra A, Barbagallo M, Pappalardo A, Colonna N, Damone L, Piscopo M, Finocchiaro P, Maugeri E, Heinitz S, Schumann D, Dressler R, Kivel N, Aberle O et al. Experimental setup and procedure for the measurement of the 7be(n,) reaction at n_TOF. Nucl Instrum Methods Phys Res, Sect A, Accel Spectrom Detect Assoc Equip. 2016;830:197–205. https://doi.org/10.1016/j.nima.2016.05.089.
15. Domingo-Pardo C, Babiano-Suarez V, Balibrea-Correa J, Caballero L, Ladarescu I, Lerendegui-Marco J, Tain JL, Tarifeño-Saldivia A, Aberle O et al. Advances and new ideas for neutron-capture astrophysics experiments at cern n_TOF. Eur Phys J A. 2023;59(1):8. https://doi.org/10.1140/epja/s10050-022-00876-7.
16. Esposito R, Calviani M, Aberle O, Barbagallo M, Cano-Ott D, Coiffet T, Colonna N, Domingo-Pardo C, Dragoni F, Franqueira Ximenes R, Giordanino L, Grenier D, Gunsing F, Kershaw K, Logé R, Maire V, Moyret P, Perez Fontenla A, Perillo-Marcone A, Pozzi F, Sgobba S, Timmins M, Vlachoudis V. Design of the third-generation lead-based neutron spallation target for the neutron time-of-flight facility at cern. Phys Rev Accel Beams. 2021;24:093001. https://doi.org/10.1103/PhysRevAccelBeams.24.093001.
17. Ferrari M, Senajova D, Aberle O, Aguiar YQ, Baillard D, Barbagallo M, Bernardes A-P, Buonocore L, Cecchetto M, Clerc V, Di Castro M, Garcia Alia R, Girod S, Grenard J-L, Kershaw K, Lerner G, Maeder MM, Makovec A, Mengoni A, Perez Ornedo M, Pozzi F, Almagro CV, Calviani M. Design development and implementation of an irradiation station at the neutron time-of-flight facility at cern. Phys Rev Accel Beams. 2022;25:103001. https://doi.org/10.1103/PhysRevAccelBeams.25.103001.
18. Gunsing F, Aberle O, Andrzejewski J et al. (The n_TOF collaboration): nuclear data activities at the n_TOF facility at cern. Eur Phys J Plus. 2016;131:371. https://doi.org/10.1140/epjp/i2016-16371-4.
19. Lerendegui-Marco J, Babiano-Suárez V, Balibrea-Correa J, Domingo-Pardo C, Ladarescu I, Tarifeño-Saldivia A, Alcayne V, Cano-Ott D, González-Romero E, Martínez T, Mendoza E, Guerrero C, Calviño F, Casanovas A, Köster U, Chiera NM, Dressler R, Maugeri EA, Schumann D. The n_TOF collaboration: new detection systems for an enhanced sensitivity in key stellar ($n,\gamma$) measurements. 2023. https://doi.org/10.48550/arXiv.2303.08701.
20. Patronis N, Colonna N et al. The CERN n_TOF NEAR station for astrophysics- and application-related neutron activation measurements. 2022. https://doi.org/10.48550/arXiv.2209.04443.
21. Patronis N, Eleme Z, Diakaki M, Tsinganis A, Vlastou R, Kokkoris M, Stamati M-E, Michalopoulou V, Stamatopoulos A, Barbagallo M, Colonna N, Heyse J, Mastromarco M, Mengoni A, Moens A, Noguere G, Praena A-J, Schillebeeckx P, Sibbens G, Tassan-Got L, Vanleeuw D. Measurement of the fission cross-section of $^{243}$Am at EAR-1 and EAR-2 of the CERN n_TOF facility. Technical report. CERN, Geneva; 2020. https://cds.cern.ch/record/2730930.
22. Praena J, Sabaté-Gilarte M, Porras I, Quesada JM, Altstadt S, Andrzejewski J, Audouin L et al. Measurement and resonance analysis of the $^{33}$S($n,\alpha$) $^{30}$Si cross section at the cern n_TOF facility in the energy region from 10 to 300 kev. Phys Rev C. 2018;97:064603. https://doi.org/10.1103/PhysRevC.97.064603.
23. Rubbia C, Andriamonje SA, Bouvet-Bensimon D, Buono S, Cappi R, Cennini P, Gelès C, Goulas I, Kadi Y, Pavlopoulos P, Revol JPC, Tzima A, Vlachoudis V. A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV: a relative performance assessment. 1998. Addendum to CERN-LHC-98-002-EET.
24. Salvatores M. Future nuclear power systems and nuclear data needs. J Nucl Sci Technol. 2002;39(sup2):4–12. https://doi.org/10.1080/00223131.2002.10875028.
25. Stamati E, Manna A, Gervino G, Bernardes A-P, Colonna N, Diakaki M, Massimi C, Mengoni A, Mucciola R, Patronis N, Vaz P, Vlastou R, Collaboration n. Neutron capture cross section measurements by the activation method at the n_TOF NEAR Station. Technical report. CERN, Geneva; 2022. https://cds.cern.ch/record/2798978.


## Publisher's Note