IL NUOVO CIMENTO **42 C** (2019) 64
DOI 10.1393/ncc/i2019-19064-3

Colloquia: EuNPC 2018

Status and perspectives of the neutron time-of-flight facility n_TOF at CERN

F. Mingrone([1]) and C. Massimi([2])([3]) on behalf of the n_TOF Collaboration([1])

([1]) *European Organization for Nuclear Research (CERN) - Geneva, Switzerland*
([2]) *Istituto Nazionale di Fisica Nucleare, Sezione di Bologna - Bologna, Italy*
([3]) *Dipartimento di Fisica e Astronomia, Università di Bologna - Bologna, Italy*

received 5 February 2019

Summary. — The neutron time-of-flight facility of CERN, called n_TOF, started its operation in 2001, and since then it plays a major role in the field of neutron cross-section measurements. The two beam-lines available provide an excellent combination of good energy resolution and high instantaneous neutron flux, combining the time-of-flight method with a powerful neutron spallation source. So far, a large number of experiments has been performed on a variety of isotopes of interest for nuclear astrophysics, advanced nuclear technologies, nuclear medicine, and for basic nuclear physics. After the CERN long shutdown, a new phase of data taking is planned to start in 2021. The R&D of a new spallation target is ongoing and its upgrade will bring important improvements in both beam lines, allowing the n_TOF Collaboration to perform new, challenging measurements.

1. – The n_TOF facility

The n_TOF facility can be considered as a high-resolution neutron spectrometer that, thanks to the time-of-flight technique, allows to measure point-wise cross-sections in a broad energy range from thermal up to GeV.

The facility ran from 2001 to 2004 (n_TOF Phase-1) and, after a four years halt due to technical issues related to the neutron-producing target, it resumed operation at the end of 2008 till the end of 2012 (n_TOF Phase-2). During the Long Shutdown 1 of CERN (LS1) a second short 20 m flight-path, complementing the existing 185 m one, has been constructed from May 2013 and completed on the 25th of July 2014, starting the n_TOF Phase-3.

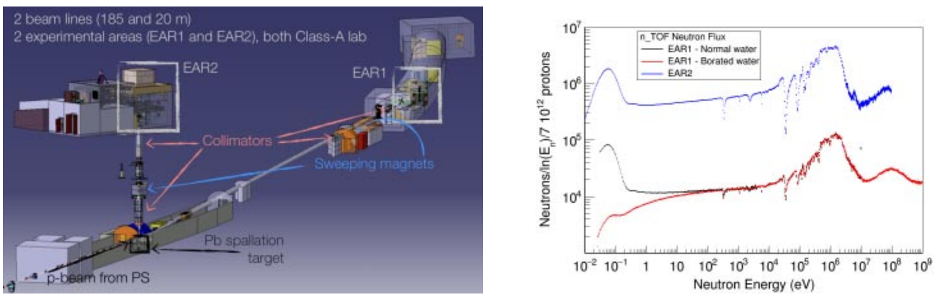
The pulsed neutron beam at n_TOF is produced by spallation of 20 GeV/c protons from the CERN Proton Synchrotron (PS) accelerator on a water-cooled lead target. Several parameters have to be taken into account to properly tune the characteristics of the proton bunches, both in terms of mechanical constraints of the lead target due to the maximum tolerable deposited power, and of performances of the neutron beam as instantaneous intensity and energy resolution.

1˙1. *n_TOF proton beam.* – The operation of the CERN PS is based on sequences of cycles 2.1 μs long, called SuperCycles. Proton bunches dedicated to different experiments (as for example those installed at the LHC) are accelerated in the machine for one or more cycles, accordingly to their characteristics in particular at extraction.

Two different types of proton bunches are carefully set up in the CERN PS to produce the n_TOF neutron beam: a dedicated bunch, with the very high intensity of about 8×10^{12} protons, and a parasitic bunch, with a lower intensity of about 3×10^{12} protons, accelerated in the PS cycle together with a second bunch for another experiment. As the PS SuperCycles have a finite length, the presence of parasitic bunches results in an increased rate of protons on the n_TOF target, i.e. a higher integrated neutron flux.

Besides the proton intensity, the other two key features of the proton beam for n_TOF are the same for both dedicated and parasitic bunches, namely the momentum - 20.32 GeV/c - and the bunch length - 25 ms at 4 σ - reached at the ejection from the accelerator. To fulfil the quoted figures, the beam is manipulated in the PS exploiting its very flexible radiofrequency system. In particular, to obtain such a short pulse a bunch rotation is performed just before the ejection from the machine, which consists in rotating the bunch in longitudinal phase space with its synchrotron frequency inside its RF-bucket. This is achieved with a sudden 180° change of phase between bucket and bunch through a modulation of the 10 MHz RF cavities, and allows to shorten the bunch length if the bunch is extracted at a proper time. Letting the bunch rotating for too long, in fact, will result in a bunch filamentation and, at the end, in a blow up of the full beam.

1˙2. *n_TOF neutron beam.* – Once ejected from the CERN PS, the n_TOF proton bunches travel in a transfer line that, through dipoles and quadrupoles, directs them onto the n_TOF spallation target. The latter, located about 20 m underground, is a cylindrical single-block of lead with a diameter of 60 cm and a thickness of 40 cm in the direction of the impinging proton beam. The target has been designed in 2008 to stand a current of about few μA from the proton beam, and therefore it is equipped with a water-cooling circuit that prevents the temperature to reach the melting value. In addition, a dedicated moderation system is present in the exit face towards the 185-m beam line, which is 4-cm thick and can host normal or borated water as moderation liquid with the purpose of widening the neutron energy spectrum down to the epithermal and thermal regions. The aim of borated water is to absorb thermal neutrons before hydrogen can



(a) (b)

Fig. 1. – (a) Scheme of the n_TOF facility. (b) Neutron flux in EAR1 (black and red lines) and EAR2 (blue line) as a function of the neutron energy. In the low neutron energy region the difference resulting in using normal (black) or borated (red) water can be seen.

TABLE I. – *Features of the n_TOF neutron beam in the experimental areas. Figures from* [1, 2].

	EAR1	EAR2
Neutron flux (n/cm^2/pulse)	about 2×10^5	about 3×10^6
Energy range	thermal to 1 GeV	thermal to few hundreds MeV
Energy resolution	$\Delta E/E = 10^{-4}$ at 10 keV	$\Delta E/E = 10^{-3}$ at 10 keV

capture them producing serious in-beam 2.2 MeV γ-ray background. As the 20-m beam line has been constructed in a following phase, its moderation circuit coincides with the cooling one and consists of 5 cm of normal water.

As schematized in Fig. 1(a), from the target two separate beam-lines start: the first, 185-m long and leading to the experimental area 1 (EAR1), is going along in the horizontal plane with an angle of 10° with respect to the impinging proton beam, while the other extends 20 m vertically on top of the target before reaching the second experimental area (EAR2). Both lines are equipped with two collimators each, of which the second is located immediately before the experimental areas to give the neutron beam its final shape. In between the two collimators a so-called sweeping magnet is placed, with the aim of deviating the remaining charged particles that are travelling along the neutron beam.

The main features of the n_TOF neutron beam at the experimental areas are summarised in Table I. As can be noted, the two experimental areas can be considered as complementary: on the one hand, EAR1 is best suited for high-resolution measurements, e.g. to study the resolved resonance region, and to extend experimental data to very high neutron energy. On the other hand, the 40 times higher neutron flux of EAR2 allows to measure the cross-sections of very low mass samples (< 1 mg), of radioisotopes with short half life, and reactions with very small cross-sections. The neutron flux of the n_TOF facility is illustrated in Fig. 1(b) for the two experimental areas [3, 4].

2. – The n_TOF facility for physics

During the operation of the facility, almost a hundred cross-sections have been measured, divided into radiative capture, fission and light particle emission reactions. The time-of-flight method permits to measure point-wise cross-sections with a very high energy-resolution and, thanks to the characteristics of the facility and its neutron source, in a broad energy range from thermal up to GeV. These cross-sections are key nuclear data inputs for a variety of calculations and simulations and are exploited, for examples, in the design of new nuclear reactors, in modelling stellar and primordial nucleosynthesis, and in optimizing nuclear medicine techniques as the Neutron Capture Therapy.

The required goals of precision and accuracy are achievable also thanks to the high-level equipments of the experimental areas. To this purpose, both the areas are classified as Class-A Laboratories, allowing therefore the usage of unsealed radioactive material with a resulting much lower background associated to the interaction of neutrons with the sample canning. In addition, a selection of the best detection system to be used is allowed thanks to the flexible design of the two areas. In this capacity a wealth of high-performance detection systems has been used at n_TOF, ranging from array of scintillators for (n,γ) reaction measurements [5, 6], to gaseous detectors as PPAC [7] for (n,f) and MicroMegas [8] for (n,f) and (n,cp) reaction measurements, to solid state

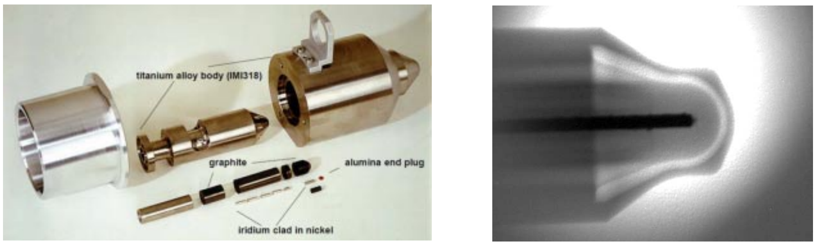


Fig. 2. – Photography of a disassembled AD Target (left) and its neutron radiography obtained at n_TOF (right). From the latter, the non-uniformity of the inner core (which should present itself as a perfect straight line) is clearly visible highlighting internal damages.

devices as silicon [9] and diamond [10] detectors for (n,cp) reaction measurements.

Recently, the n_TOF EAR2 has been exploited as a neutron imaging facility, paving the way to applications beyond neutron-induced reaction measurements: an Antiproton Decelerator Target has been inspected with the goal to assess the integrity of its iridium inner core after proton irradiation. As can be seen in Fig. 2, the radiography successfully pointed out potential damages in the core, which would not have been visible with an X-ray radiography due to the titanium alloy container of the target.

3. – Conclusions and perspectives

The unique role of the n_TOF facility in providing high-quality nuclear data is well assessed, with lots of important neutron-induced reaction cross sections having been measured during the facility operation [11]. During the Long Shutdown 2 of CERN (LS2) several upgrades are foreseen to ameliorate the facility performances and further exploit its potential. In particular, three macro areas of development could be identified. Firstly, the proton beam - target assembly: a new target is under development and will be installed during LS2. It will be able to stand a higher power deposited by the proton beam, with the consequent possibility of increase the proton bunch intensity - and therefore the instantaneous neutron flux - up to 10^{13} proton per pulse. Secondly, the neutron beam-lines will be optimized to enable applications beyond neutron-induced reaction measurements, as neutron imaging and neutron irradiation station. Last, a diversity of detection techniques is under development, as Ge detectors for γ spectrometry, detectors able to use gaseous targets, and position sensitive detectors for (n,γ) measurements.

REFERENCES

[1] Guerrero C. *et al.*, *Eur. Phys. J. A*, **49** (2013) 27.
[2] Weiss C. *et al.*, *Nucl. Inst. and Meth. A*, **799** (2015) 90.
[3] Barbagallo M. *et al.*, *Eur. Phys. J. A*, **49** (2013) 156.
[4] Sabaté-Gilarte M. *et al.*, *Eur. Phys. J. A*, **53** (2017) 210.
[5] Guerrero C. *et al.*, *Nucl. Inst. Meth. A*, **608** (2009) 424.
[6] Borella A. *et al.*, *Nucl. Inst. Meth. A*, **577** (2007) 626.
[7] Paradela C. *et al.*, *Phys. Rev. C*, **82** (2010) 034601.
[8] Andriamonje S. *et al.*, *Journal of Instrumentation*, **5** (2010) .
[9] Consentino L. *et al.*, *Nucl. Inst. Meth. A*, **830** (2016) 197.
[10] Weiss C. *et al.*, *Nucl. Inst. Meth. A*, **732** (2013) 190.
[11] Dupont E. *et al.*, *EPJ Web of Conferences*, **146** (2017) 07002.