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Design, testing, commissioning, and early operation of the third-generation n_TOF neutron spallation target at CERN

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Abstract. The n_TOF facility at the European Laboratory for Particle Physics (CERN) is a top-class, high-brightness neutron spallation source dedicated to high-resolution neutron time-of-flight experiments. During CERN's Long Shutdown 2 (LS2, 2019-2021), the facility's neutron spallation target was upgraded and is now operating with its third-generation target. The target is based on a pure-Pb core cooled by gaseous nitrogen and has been designed to withstand the impact of a 20-GeV/*c* proton beam in bunches of 10^{13} protons with a bunch duration of 6-8 ns RMS. The produced neutrons span 11 orders of magnitude in kinetic energy (from thermal to GeV) and are delivered to two experimental areas and a neutron irradiation station near the target. This contribution includes a description of the physics and engineering design processes that brought the facility from its second-generation target to its current third-generation target, the planned autopsy of the second-generation target in 2023 to investigate its status after 10 years of operation, tests under beam irradiation carried out on target prototypes at CERN's HiRadMat facility, and the commissioning with beam of the new target, as well as the challenges encountered during the first year of its operation.

1 Introduction on the n_TOF facility

The neutron time-of-flight (n_TOF) facility operates at the European Laboratory for Particle Physics (CERN) in Geneva, Switzerland. It is composed of a pure-lead based neutron spallation target coupled to two neutron flight paths and two experimental areas for neutron time of flight experiments [1]. There is also a neutron irradiation and measurement station located close to the target [2, 3].

The CERN's Proton Synchrotron (PS) delivers 20-GeV/*c* protons to the target, producing neutrons through the nuclear spallation process. These neutrons travel towards two experimental areas: Experimental Area 1 (EAR1) located 185 m behind the target, and Experimental Area 2 (EAR2) located 20 m above the target (Fig. 1).

The PS is currently able to deliver short bunches with a maximum of 8.5×10^{12} protons in 6-8 ns (RMS) to the target, with a minimum period between bunches of 1.2 s. The number of neutrons reaching the experimental areas is on the order of 10^6 n/cm^2 per bunch in EAR1 and 10^8 n/cm^2 per bunch in EAR2.

The neutrons generated by the spallation process are moderated by two water layers: 4 cm of borated water (1.28 wt% of ^{10}B) for the neutrons directed towards EAR1, and 3.4 cm of demineralized water for the neutrons directed towards EAR2.

Thanks to the neutron moderation, a wide neutron energy spectrum is available for the two experimental areas, ranging from thermal energy up to 1 GeV. Moreover, the long flight paths provide high energy resolution ($\Delta E/E = 10^{-4}$ in EAR1 [4, 5]). These features make the n_TOF facility ideal for high signal-to-background ratio measurements of neutron cross-sections of radioactive isotopes, even if they are available in tiny amounts.

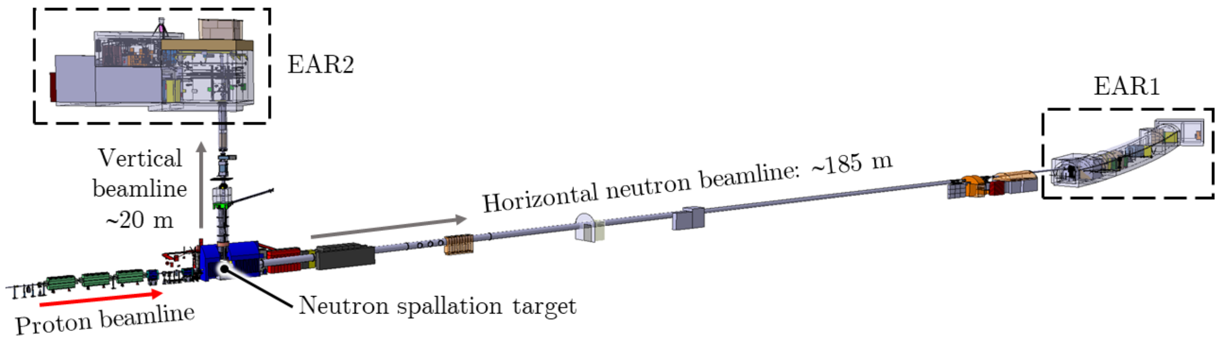

Fig. 1. The n_TOF facility. A pulsed 20 GeV/*c* proton beam interacts with a lead-based neutron spallation target, producing neutrons that travel along two flight paths toward two experimental areas equipped with appropriate detectors for time-of-flight measurements.

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2 The third-generation n_TOF target

The final design of the third-generation target (Fig. 2) consists of a series of pure-lead (>99.9 wt%) plates cooled by nitrogen gas [6] at slightly above atmospheric pressure. The use of a gaseous coolant instead of a liquid one was motivated by corrosion and erosion issues encountered during the operation of the first and second-generation targets, which were water-cooled in direct contact with lead. Since pure lead is highly susceptible to creep deformation, the lead plates are supported by an anti-creep structure made from aluminum alloy 6082-T6. The target core is contained in a stainless-steel vessel, and the water moderator vessels are made from aluminum alloy 5083. The EAR1 aluminum moderator vessel is directly bonded to the stainless-steel vessel via explosion welding, with intermediate layers of pure aluminum and titanium between stainless steel (vessel side) and aluminum 5083 (moderator side). The target was originally designed with the beam parameters from Table 1 as a reference.

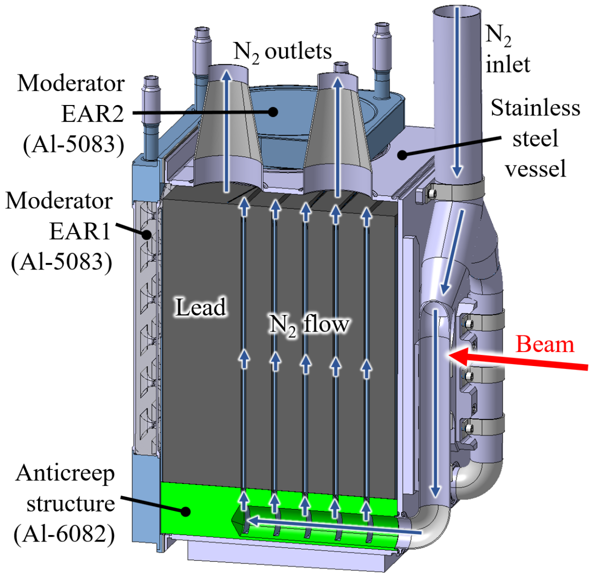

Fig. 2. The third-generation n_TOF target (sectional view). Six pure-lead (>99.9 wt%) plates are supported by an aluminum 6082-T6 anti-creep structure. Pure nitrogen gas flows in the channels between the lead plates to cool them. The target core is enclosed in a stainless-steel vessel. The two moderator vessels are made from aluminum 5083, and the EAR1 moderator vessel is directly bonded to the stainless-steel vessel via explosion welding.

Table 1. Beam parameters used as a reference in the design of the third-generation n_TOF target.

Bunch intensity	10^{13} p^+
Beam momentum	20 GeV/*c*
Bunch energy	32 kJ
Bunch length	25 ns (4σ)
Beam size (Gaussian)	15 mm (1σ)
Average intensity	1.67×10^{12} p^+/s
Average current	0.27 µA
Average power	5.4 kW
Peak current	91.3 A
Peak power	1.8 TW

3 Thermo-mechanical behavior

The third-generation neutron target has been in operation since July 2021. The design studies for this new target began in 2015 taking into account the operational experience of previous spallation targets and analysis of different target concepts based on materials such as lead, tantalum, and tungsten, as well as cladding layers of tantalum, titanium Grade 5, and Inconel. Various cooling fluids were also compared, including water, air, nitrogen, and argon. A more detailed summary of the design solutions explored and the rationale behind the final target design can be found in Ref. [7].

To evaluate the performance of each design solution, Monte Carlo simulations (primarily using the FLUKA code [8, 9]) were performed to estimate the physics performance (e.g., neutron flux, energy resolution, photon background) and the heat distribution induced in the target by interaction with the proton beam. Computational Fluid Dynamics (CFD) simulations were used to estimate the heat removed per unit of surface area and temperature gradient (Heat Transfer Coefficient, HTC) by the target cooling system. The heat distribution generated by the beam - target interaction and the HTC map on the target surfaces were used as boundary conditions for Finite-Element (FE) thermal analyses, which provided the time evolution of the temperature distribution in the examined target solutions. This resulting temperature distribution was then used as boundary condition for Finite-Element structural analyses to estimate the time evolution of the stress distribution in the target during operation.

The results of these studies showed that each instantaneous temperature rise caused by a beam impact leads to a rapid thermal expansion of the target core followed by the propagation of plastic stress waves inside the target. The temperature distribution in the target and the resulting stresses from stress-wave propagation are the main factors to consider when assessing the thermo-mechanical integrity and fatigue resistance of the target [10].

In the final design, and with the beam parameters listed in Table 1, thermal simulations (see Fig. 3) estimate a peak temperature of 135°C inside the lead plates in the worst-case scenario (six consecutive bunches impacting the target, separated by 1.2 s and followed by a cooling period of 30 s). Structural finite-element simulations revealed that the peak von Mises stress in the pure lead plates is 2.6 MPa, indicating that the material operates within the elasto-plastic regime. As a result, the material may be susceptible to cyclic plasticity and fatigue damage during the target's lifetime, which spans millions of cycles (10 million cycles were considered for fatigue calculations). To validate the target's ability to perform its intended function over its entire lifespan, a test of a prototype of the target under beam irradiation was conducted at the HiRadMat facility at CERN. The test is described in Section 5.

4 Modeling of creep behavior

Creep deformations of pure lead represent a critical aspect of the target's thermo-mechanical behavior as pure lead could deform into the cooling channels, partially blocking them and compromising the cooling efficiency. A dedicated material constitutive model was implemented in the Finite-Element codes to simulate the creep behavior of lead under the different conditions of stress and temperature that can be found in the target during operation. The model is based on creep data for lead provided in Ref. [11]. It consists of a series of piecewise functions, each composed of multiple power laws (Fig. 4):

$$\dot{\varepsilon} = c\,\sigma^{n} \quad (1)$$

where $\dot{\varepsilon}$ is the plastic strain-rate due to creep, σ is the von Mises equivalent stress, c and n are coefficients whose values best fit the available data. The coefficient n is close to 1 when the main mechanism of creep flow is diffusional flow, while it can reach values between 5 and 7 in the case of power-law creep. Each curve in Fig. 4 is valid for a specific temperature; values for intermediate temperatures are obtained by logarithmic interpolation.

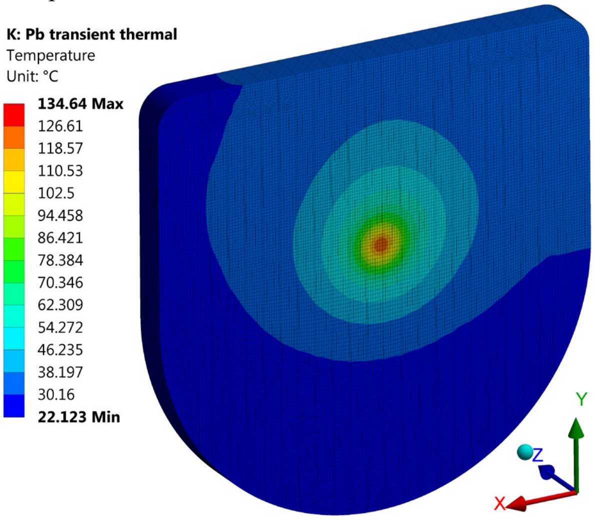

Fig. 3. Peak temperature distribution in the target [6]. The image shows the model of the second lead plate, where a peak temperature of 135°C is reached. The parameters of the beam load are listed in Table 1.

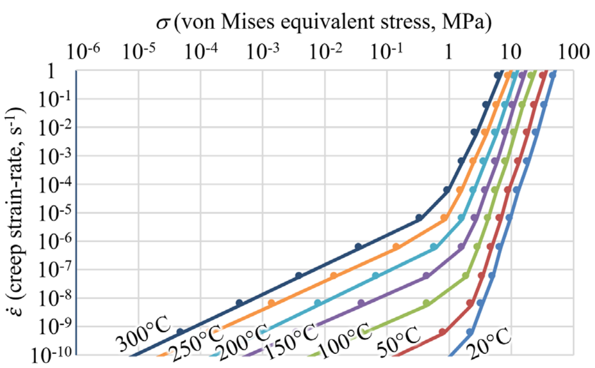

Fig. 4. Constitutive model for pure-lead creep implemented in Finite-Element code. It consists of a series of power laws. Curves for intermediate temperatures are obtained by logarithmic interpolation. Data from Ref. [11].

The proposed creep model has been implemented in Finite-Element codes to simulate the creep deformations in the target after 6 years and 4 months of continuous operation (twice the expected target's lifetime) under a steady peak temperature field. The maximum lead penetration into a cooling channel was found to be 0.64 mm, whereas the depth of the cooling channels is 3 mm (see Fig. 5). Accident scenarios, including the possibility of fully obstructed channels, were considered in CFD simulations. The results of this analysis showed that the target's operation would not be compromised: the new peak temperature would be equal to 160°C, which is considered acceptable for the accident scenario examined.

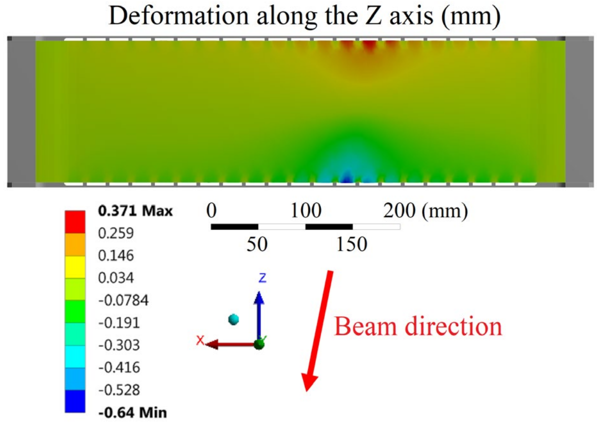

Fig. 5. Simulation of creep deformation in the lead target [6]. Sectional view from above. The maximum penetration of lead into a cooling channel is 0.64 mm, in the sixth lead plate.

5 Tests under beam irradiation

A small-scale prototype of the third-generation target was tested at the HiRadMat facility at CERN. The prototype consisted of six pure-lead blocks enclosed in an aluminum vessel filled with nitrogen gas. It was irradiated with 440-GeV/c proton-beam pulses from the CERN's Super Proton Synchrotron (SPS), with a maximum of 3.5×10^{13} protons delivered in short pulses of 8 µs [12].

The prototype was hit by 1500 proton-beam bunches of 4–4.5×10^{12} protons with a period of 22.8 s and a beam size of 4 mm RMS. These parameters were chosen to induce in the prototype a slightly higher fatigue damage than the one induced in the n_TOF third-generation target under the nominal beam loads described in Table 1. The temperature of the lead blocks was monitored by thermocouples and used to automatically control heating foils that were glued to the aluminum container to maintain the desired temperature range of 100–140°C. This temperature range is the one estimated by the thermal simulations described in Section 3 and Fig. 3.

The pure-lead blocks were inspected by neutron tomography at the Paul Scherrer Institut (PSI) with an image resolution of 100 µs. No defects were detected inside the material, confirming the soundness of the target design and its ability to produce neutrons for the facility for another decade.

6 Commissioning with beam

The new target began operating in July 2021. The profile of the proton beam is monitored using a Secondary Emission Monitor (SEM) grid. According to the design assumptions in Table 1, a beam size of 15 mm was expected. However, during the commissioning with beam of the new target, the beam size appeared to be too large for the vertical aperture of one of the bending dipoles upstream of the target. This led to beam losses and a high dose rate in the area. The beamline was temporarily operated with a narrower beam on the vertical axis (7 mm RMS), which was not acceptable for the long-term integrity of the target. The issue was solved by removing the last two focusing quadrupoles upstream of the target from the proton beamline during the 2021-2022 winter CERN's accelerator stop. This enabled the optimization of the beam optics and the possibility to deliver a larger beam spot on the target with contained beam losses. As a result, the beam spot measured at the SEM grid had a size of 27 mm along the horizontal axis and 15 mm along the vertical axis. This beam size is now even larger than the one in the design assumptions of Table 1, enabling an increase in the average intensity on target up to 2.3×10^{12} p^+/s (7.4 kW).

7 Conclusions

The third-generation n_TOF target has been successfully operational since July 2021. Thermo-structural simulations were used to simulate the target's response when impacted by high-intensity beam pulses. These simulations revealed that the temperatures and stresses reached during operation bring the pure lead in the target into elasto-plastic regime, raising concerns about cyclic plasticity and fatigue damage. A test was designed and performed with a prototype under beam irradiation to validate the target's capability to maintain its integrity under repeated beam impacts, which was successfully validated. Simulations were exploited to design the test in a way that the estimated fatigue damage in the prototype would reproduce that of the target operating under nominal conditions, with some margin for conservatism. Additionally, a new material constitutive model was implemented in the FE software to estimate creep deformations. This was done because of concerns that creep deformation could obstruct cooling channels and impair cooling efficiency, but simulations showed that the deformations were acceptable and the obstruction was contained within acceptable limits. Finally, similar simulations were employed to estimate the consequences of accident scenarios and confirmed that there would be no catastrophic consequences.

A better understanding of the plastic deformations induced in the target by creep and beam impacts will be achieved by examining the second-generation target, also based on pure lead. This target operated from 2008 to 2018 [7] and has a different geometry, with the core made of a single massive lead cylinder with a diameter of 60 cm and a length of 40 cm; it was cooled by water rather than nitrogen gas. Despite the different geometry, the examination of the lead surfaces of the spent target can contribute to the validation of the estimations of the plastic deformations due to creep and beam impacts on the target. The lead target core is enclosed in an aluminum vessel, which includes the target's borated-water moderator vessel. To expose the surfaces of the lead core, the aluminum vessel must be machined. One base of the lead cylinder will be exposed by machining the side of the vessel directly impacted by the proton beam, while the other base of the cylinder will be exposed by machining the moderator vessel. Due to the high radioactive dose around the target, the procedure will be executed by robots. The removed moderator vessel will be inspected to assess the presence of deposited boron from the borated water and pitting corrosion effects. The exposed lead surfaces will then be scanned by a 3D laser scanner, providing the lead surface deformations due to creep and beam impacts after 10 years of target operation.

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