DESIGN OF THE NEW CERN n_TOF NEUTRON SPALLATION TARGET: R&D AND PROTOTYPING ACTIVITIES

R. Esposito[1], M. Bergeret, M. Calviani, T. Coiffet, M. Delonca, L. Dufay-Chanat, E. Gallay,
L. Gomez Pereira, M. Guinchard, D. Horvath, T. Koettig, F. Latini, A. P. Perez,
A. T. Perez Fontenla, A. Perillo Marcone, S. Sgobba, M. Timmins, A. Vacca, V. Vlachoudis,
CERN (European Organization for Nuclear Research), 1211 Geneva 23, Switzerland
R. Logé, EPFL (École Polytechnique Fédérale de Lausanne), 1015 Lausanne, Switzerland
[1]also at EPFL (École Polytechnique Fédérale de Lausanne), 1015 Lausanne, Switzerland

Abstract

A new spallation target for the CERN neutron time-of-flight (n_TOF) facility will be installed during Long Shutdown 2 (LS2, 2019-2020). The objective of the new design is to improve operational reliability, avoid water contamination from spallation products, corrosion/erosion and creep phenomena, as well as optimizing it for the 20 meter distant vertical Experimental Area 2, whilst keeping at least the same physics performances of the current target at the 185 meter distant Experimental Area 1. Several possible target solutions have been studied with FLUKA Monte Carlo simulations in order to find the optimal set of parameters in terms of neutron fluence, photon background, resolution function, energy deposition and radiation damage. Thermo-mechanical studies (including CFD simulations) have been performed in order to evaluate and optimize the target ability to withstand the beam loads in terms of peak temperatures, cooling system efficiency, maximum stresses, creep and fatigue behaviour of the target materials, leading to a preliminary mechanical design of the target.

This paper also covers the prototyping and material characterization activities carried out in order to validate the feasibility of the investigated solutions.

INTRODUCTION: THE n_TOF FACILITY

The n_TOF facility [1] at CERN is a neutron source coupled to two flight paths. A pure lead neutron spallation target is impacted by a pulsed 20 GeV/c proton beam coming from the CERN Proton Synchrotron (PS). The generated neutrons travel along two flight paths inside vacuum pipes directed towards two experimental areas (EAR1 and EAR2): a 185 m long horizontal path and a 20 m long vertical path above the target, respectively.

The facility has been designed to study neutron-nucleus interactions for a wide range of neutron kinetic energies (from few meV to several GeV). The neutron kinetic energy is determined by their time-of-flight, hence the name n_TOF. The neutron spectrum is modified by a sequence of two moderators, constituted by light water as well as borated water (1.28% wt) to reduce the gamma background in EAR1 [1].

THE NEW n_TOF TARGET

The n_TOF facility will undergo an important consolidation during LS2, which will also include the upgrade of the target [2].

The current n_TOF target core (*target #2*) is a pure lead, water cooled $\varnothing 600\,\mathrm{mm} \times 400\,\mathrm{mm}$ cylinder. The purpose of the target upgrade is to solve and/or improve some critical aspects of the current target:

- Leaching of lead by erosion-corrosion inducing contamination with target spallation products of the cooling water in direct contact with lead.
- Thin (600 μm) aluminium window separating water of the cooling and moderator circuits, subject to risk of pitting on the moderator side.
- Beam intensity on target limited to 1.66×10^{12} p^+/s (~5 kW) in order to maintain the target surface temperature low enough and make sure that the water chemistry is always respecting the tight operational constraints required.
- Target design not optimal in relation to neutron fluence to EAR2.
- Creep phenomena in lead.

The New n_TOF Target Design

Several possible design solutions have been considered and studied for the new target (*n_TOF target #3*). Starting from physics performance studies [2], a first selection

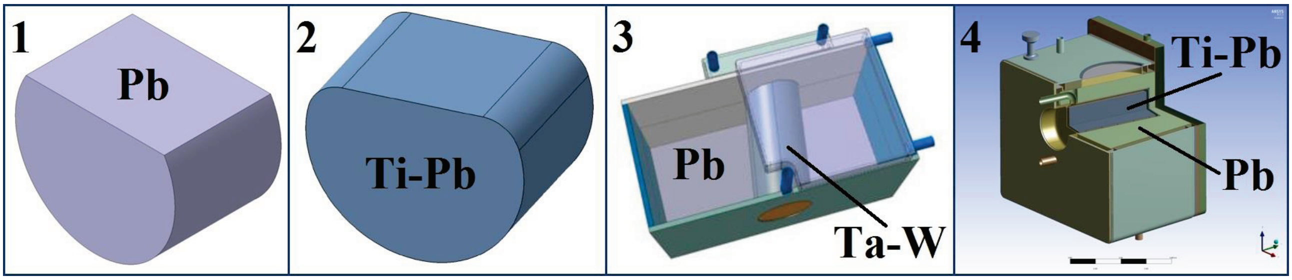

Figure 1: n_TOF target #3 design solutions.

converged on four possible designs (Fig. 1):

1. Pure Pb with horizontal cut
2. Ti-contained Pb with horizontal cut
3. Ta-cladded pure W core embedded in Pb block
4. Ti-contained Pb core embedded in Pb block

The **first solution** is similar to the current target, a ∅600 mm × 400 mm pure Pb cylinder. The new solution includes a horizontal top cut 150 mm far from the cylinder axis in order to increase the neutron fluence to EAR2 without compromising neutron fluence to EAR1. This design could be considered as a backup solution in case the other solutions turn out to be unfeasible, since it does not solve the issues related to water circuit contamination, target erosion corrosion and creep phenomena.

The **second solution** is similar to the first one, a pure Pb cylinder with a horizontal cut. In this new solution the Pb block is enclosed in a 1 mm - 2 mm thick titanium alloy (Ti-6Al-4V) shell, which protects the Pb core from erosion corrosion and creep phenomena, as well as the cooling water from Pb contamination. One critical point of this solution is to manufacture the target guaranteeing a good thermal contact between the Pb core and the Ti casing, since Pb is no longer cooled by direct contact with water. An additional critical point is to keep mechanical stresses in the Ti layer well below its yield strength and compatible with a target fatigue life corresponding to 4×10^7 pulses (equivalent to about ten years of operation). The thickness of the Ti casing is limited to 0.5 mm - 2 mm (depending on which face is considered) by physics requirements, especially reduction of gamma background that can perturb the neutron capture measurements. An added advantage of this solution is that the target failure is linked to the failure of the Ti case only and not of the pure lead core, which has poor mechanical properties compared to Ti-6Al-4V and which could safely fail during operation without compromising the target integrity.

The **third solution** is constituted by a tantalum-cladded tungsten (by HIP process) core embedded in a massive pure lead block. The Ta-cladded W core is a ∅100 mm × 250 mm cylinder which absorbs most of the beam power and is cooled by a dedicated high-efficiency water cooling circuit, contained in a stainless steel or aluminium alloy envelope. The Ta cladding thickness is around 1 mm - 2 mm. The external Pb block has a size of 500 mm × 500 mm × 350 mm: due to the residual power deposited in tis mass, an air cooling system is required to cool it. The most critical point of this solution consists in higher gamma background produced by the presence of the tungsten core as well as a lower neutron fluence to EAR1 if compared to the other solutions [2].

The **fourth solution** is composed by a titanium-contained lead core embedded in a lead block. The core is a ∅150 mm × 400 mm cylinder cooled by a dedicated high-efficiency water circuit. The Ti case thickness can be between 0.5 mm and 3 mm, depending on which face is considered. The external lead block size is 600 mm × 500 mm × 450 mm. In addition, this lead mass is air-cooled and separated from the cooling water by a stainless steel or aluminium envelope.

CFD and Thermo-mechanical Analyses

Preliminary CFD and thermo-mechanical analyses have been performed for each solution in order to estimate the cooling efficiency and the target ability to withstand the required beam loads.

The beam parameters listed below have been assumed:

- Proton energy: 20 GeV/c
- Beam transverse size (1σ, x and y): 15 mm
- Number of protons per pulse: 10^{13}
- Number of pulses: 14 per supercycle
- Minimum pulse period: 1.2 s
- Supercycle length: 36 s
- Average intensity: 3.89×10^{12} p^+/s
- Pulse energy: 32 kJ
- Average power: 12.5 kW

Physics optimization of the four target solutions has been performed by means of simulations with FLUKA Monte-Carlo code [2], which provided as well the energy deposition distributions in the target materials to use as load input for thermo-structural analyses.

By means of CFD studies, heat transfer coefficient (HTC) fields linked to the water cooling system have been estimated to range from 170 W/(m^2 K) to 3000 W/(m^2 K) for the first two solutions and from 500 W/(m^2 K) to 5000 W/(m^2 K) for the other two solutions (assumed flow rate: 7 m^3/h). For the external Pb blocks of solutions 3 and 4, the estimated HTC is between 2.5 W/(m^2 K) and 50 W/(m^2 K), assuming a flow rate of air of 50 m^3/h. Such HTC fields have been used as boundary conditions for the thermal analyses.

Table 1 and 2 summarise the key thermo-structural results for the four design solutions, where:

- T_{max}: maximum temperature
- T_m: melting temperature
- $\sigma_{eq,\,max}$: maximum equivalent von Mises stress
- $\sigma_{1,\,max}$: maximum principal stress
- $\Delta\sigma$(4e7, R=0): Fatigue strength stress range at 4×10^7 cycles and stress ratio equal to 0.

Table 1: Thermal Analyses Results

Solution	Material	T_{max} [°C]	T_m [°C]
1	Pb	156	322
2	Pb	150	322
	Ti-6Al-4V	79	1610
3	W	94	3410
	Ta	54	2990
	Pb	55	322
4	Pb	187	322
	Ti-6Al-4V	35	1610

The only value of stress that is higher than the fatigue strength at 4×10^7 cycles is the maximum principal stress in Pb in solution 1. Further studies are required for this solution in order to estimate less conservatively the actual sequence of stress cycles, which is related to the real operation of the target.

Table 2: Structural Analyses Results

Solution	Material	$\sigma_{eq,\,max}$ [MPa]	$\sigma_{1,\,max}$ [MPa]	$\Delta\sigma$ (4e7, R=0) [MPa]
1	Pb	2.32	5.75	4.4
2	Ti-6Al-4V	143	159	339
3	W	81	68	535
	Ta	32	32	66
4	Ti-6Al-4V	250	270	339

PROTOTYPING ACTIVITY

A wide prototyping activity is being carried out in order to verify the feasibility of the new design solutions and to find the optimal production processes from the point of view of manufacturability and target performance. Four small-scale prototypes have been realized for the Ta-cladded W solution and two prototypes for the Ti-contained Pb solutions. One more small-scale Ti-contained Pb prototype is being currently produced and three more prototypes are planned to be realized regarding this solution.

Tantalum-cladded Tungsten Prototypes

The four Ta-cladded W prototypes are ∅4.5 mm × 8 mm cylinders obtained by hot isostatic pressing (HIP). The tantalum shell is 2 mm thick. Ultrasound, die penetrant and optical microscope observations have been performed on the prototypes to examine the quality of the bond at the interface between Ta and W [3]. Aside from small isolated defects, the bond quality appears to be excellent, hence a perfect thermal transfer can be assumed at this interface (Fig. 2).

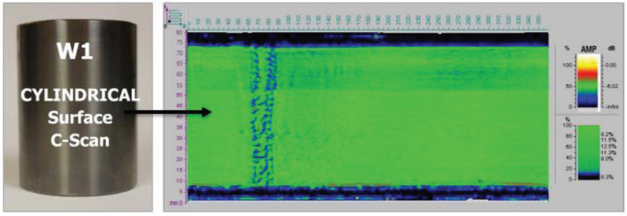

Figure 2: Ta-W prototype ultrasound tests.

Titanium-contained Lead Prototypes

The Ti-contained Pb prototypes are composed by ∅150 mm × 100 mm lead cylinders contained in a 2 mm or 3 mm shell of Ti-6Al-4V (Fig. 3). The two prototypes already realized have been produced by two different technological processes: the first one has been obtained by cryogenic shrink fitting whilst the second one by casting lead into the Ti container. A series of strain gauges has been applied to the Ti cylinder to measure in real time the values of stress in the Ti case. Such values are also an indirect indication of the level of contact pressure at the interface. Both prototypes showed that, according to strain gauge measurements, it is possible to obtain a good contact pressure at the cylindrical interface. This observation has been confirmed by high-energy radiographies at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France.

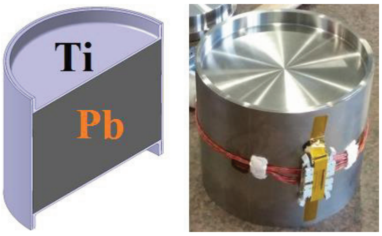

Figure 3: Sketch and picture of the Ti-Pb n_TOF target prototype.

After the cryogenic shrink fitting process for the first prototype and the lead casting process for the second prototype, Ti lids have been pressed on the Pb blocks and welded by electron beam welding to the Ti cylinders in order to totally enclose the Pb blocks. After this process, a lack of contact and presence of a gap were observed on the interface between the Pb block and the Ti lids, due to high bending of the thin lid subject to the pressure of the Pb block on the outlying surface of it. An improvement has been obtained with the second prototype, where a good depression thanks to vacuum between the Ti lid and the Pb block has been assured in order to help keeping a good contact at the interface.

In order to further improve the contact quality at the Ti lids, a third prototype is being realized (Fig. 4) in which a beryllium plate will be integrated in each lid to make it stiffer and reduce is bending. Beryllium does not interfere with target performance and does not increase the gamma background for the experiment.

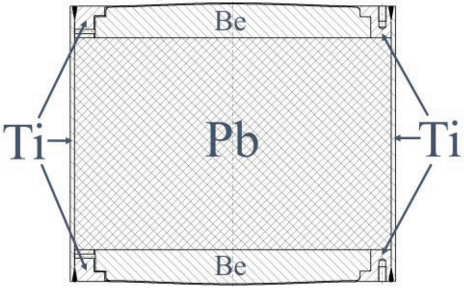

Figure 4: Prototype 3 sketch.

In any case, it has been estimated by FEM simulations that for solution 4 a good contact at the lids is not strictly required and it does not compromise the target operation.

Three more Ti-Pb prototypes are planned to be realized:

1. Ti-Pb prototype with Be inserts totally encapsulated in Ti thin plates.
2. Ti-Pb prototype with Ti lids and Pb bonded by explosion bonding process.
3. Ti-Pb prototype with Be inserts and Inconel replacing titanium alloy. Inconel can be bonded to the Be plates by brazing process.

REFERENCES

[1] n_TOF, `https://ntof-exp.web.cern.ch`

[2] M. Calviani *et al.*, “Preliminary conceptual design of the n_TOF spallation target #3”, CERN, Geneva, Switzerland, Tech. Note TOF-TAR-EN-0001, Mar. 2016.

[3] L. Gomez Pereira *et al.*, “Quality inspection of potential material target for n_TOF”, CERN, Geneva, Switzerland, Rep. EDMS 1749441, Jan. 2016.