ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF084

DESIGN, PROTOTYPING ACTIVITIES AND BEAM IRRADIATION TEST FOR THE NEW n_TOF NEUTRON SPALLATION TARGET

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Abstract

A third-generation neutron spallation target for the neutron time-of-flight facility at CERN (n_TOF) is currently undergoing the design and prototyping stage. The new design aims at improving reliability, increasing beam intensity on target and avoiding issues encountered in the current generation target, in particular the contamination of the cooling system water with radioactive spallation products coming from washing out lead. After a preliminary design and an initial prototyping stage [1], a baseline solution has been defined consisting in a pure lead target core contained in a Ti-6Al-4V cladding and embedded in a massive Pb block. A backup solution has also been defined, consisting in a Ta-cladded W core embedded in a Pb block. Both solutions are currently undergoing the detailed design stage. This contribution details the prototyping activity, the robustness studies for accidental scenarios and the design of a beam irradiation test on prototypes of the target core.

THE NEW n_TOF TARGET

The n_TOF neutron spallation source [2] is composed of a pure lead target impacted by a pulsed 20 GeV/c proton beam from the CERN *Proton Synchrotron* (PS). The generated neutrons travel inside vacuum pipes along two flight paths 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 current target core is a pure lead, water-cooled monolithic cylinder with a diameter of 60 cm and a length of 40 cm [3]. A new target will be installed during Long Shutdown 2 (2019-2020). The new target must be designed to:

- Withstand a higher average beam intensity (2.7×10^{12} p^+/s), limited to 1.66×10^{12} p^+/s in the current target.
- Withstand a higher instantaneous beam intensity (10^{13} protons in a single 7 ns proton pulse).
- Optimize the neutron flux towards the two experimental areas [4].
- Avoid contamination of the cooling water with radioactive spallation products from lead due to erosion-corrosion phenomena (observed in the current target [5]).

The baseline design for the new target (Figure 1) currently consists of a ∅150 mm × 330 mm cylindrical core composed of a pure Pb cylinder contained in a 1.5 mm Ti-6Al-4V envelope. This core is the part of the target directly impacted by the proton beam, thus accounting to almost 70% of the power dissipated into the target. For this reason, it needs a dedicated high-efficiency water cooling circuit to keep its temperature within acceptable values. The impact of a 7 ns high-intensity proton pulse generates stress waves which propagates in the lead core, which are an issue for the material integrity. The Ti-6Al-4V layer protects the inner lead from corrosion-erosion phenomena and contains it in case of cracks or other material failure mechanisms in lead due to stress waves. This core is embedded in a 600 mm × 500 mm × 492 mm lead block, for which a nitrogen gas cooling system is sufficient since the distribution of dissipated power is more spread out and represents only about 30% of the total power absorbed in the target. A variation of this solution without Ti-6Al-4V cladding and with nitrogen cooling (to avoid corrosion-erosion phenomena) is also being considered.

A possible backup design consists of a water-cooled, ∅100 mm × 250 mm tantalum-cladded tungsten cylindrical core embedded in a larger nitrogen-cooled lead block. Also in this case, the role of the core part is to absorb the majority of the dissipated power. The Ta-W solution is characterised by higher mechanical strength and cooling efficiency but worse physics performances (lower neutron yield, higher gamma background) [4], [5].

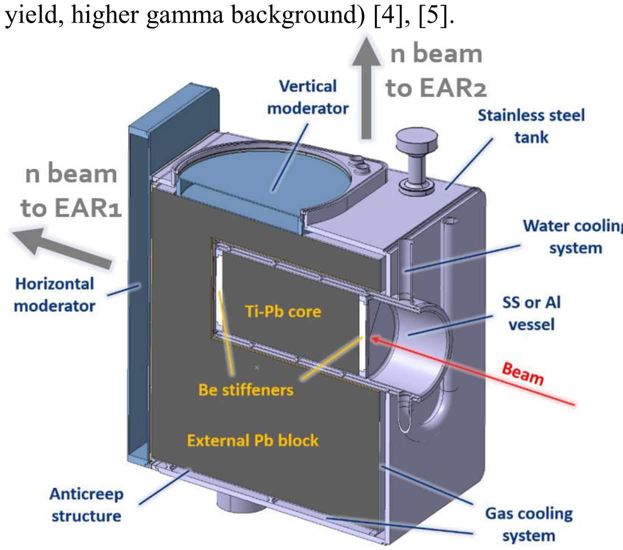

Figure 1. n_TOF target baseline design.

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TARGET PROTOTYPING

For both design solutions, since the water of the cooling circuit is in direct contact with the external layers (tantalum and Ti-6Al-4V) rather than the core materials (tungsten and lead), a good thermal contact between them plays a fundamental role for an effective heat dissipation. The bonding between tantalum and tungsten is obtained by diffusion bonding through a manufacturing process of Hot Isostatic Pressing (HIPing) [6]. The quality of the bond obtained by this process has been tested and validated by ultrasonic inspections and scanning electron microscopy [7, 8], as well as being successfully used in other target facilities. Such a technique ensures an excellent thermal contact between core and cladding materials. In the case of the Ti-6Al-4V-cladded lead target, the two materials are not physically bonded but only subjected to mechanical contact, thus the thermal conductance between them is guaranteed only by an adequate pressure at the contact interface. An extensive prototyping activity has been carried out at CERN to identify the design and the manufacturing process that would guarantee the best results in terms of thermal contact at the interface between titanium alloy and lead. Two processes have been simulated by FEM, tested and validated [1]:

1. Casting followed by machine pressing of the block inside a Ti-6Al-4V container.
2. Cryogenic shrink fitting of the lead cylinder inside a Ti-6Al-4V shell.

The two lead cylinders are then completely sealed in a Ti-6Al-4V container by electron beam welding one tita-nium lid for the casted lead solution and two lids for the cryogenic shrink fitting solution to the rest of the assembly. The two prototypes have been examined by high-energy X-ray radiography at *European Synchrotron Radiation Facility* (ESRF) in Grenoble [9] to identify the presence (or not) of gaps at the lead-titanium interface. The results have been compared with predictions obtained by simulating the manufacturing process of the prototypes. A good numerical-experimental correlation has been observed (Figure 2) showing that, due to the low bending stiffness of the thin titanium lids, there are gaps and loss of contact at the interface.

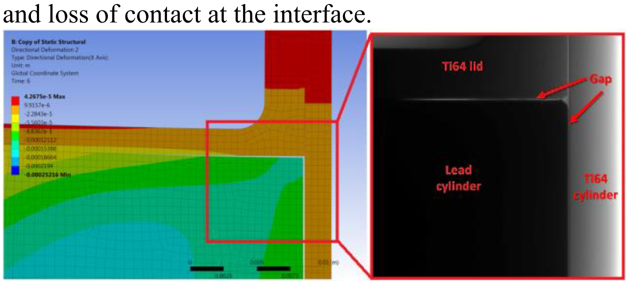

Figure 2. Comparison between simulated Ti-Pb prototype manufacturing process and X-ray inspection results.

A third prototype has been produced, equipped with stiffening plates integrated into the titanium lids to limit their deformation. The stiffening plates are made of beryllium to not increase too much the experimental background (Figure 3). The mechanical and thermal contact between titanium lids and beryllium plates is guaranteed by a specific beryllium surface profile at the interface.

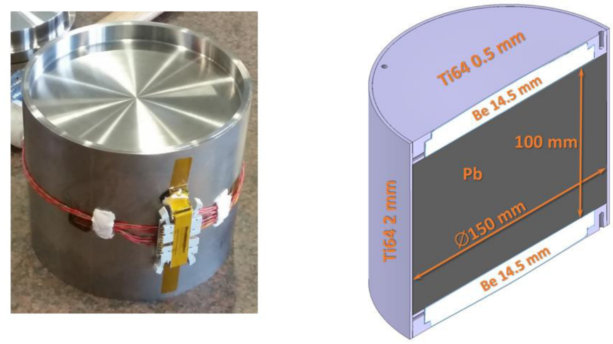

Figure 3. Ti-Pb prototype with beryllium inserts.

The optimal profile of the beryllium surface at the contact interface with the Ti-6Al-4V lid has been designed with the help of finite element simulations so that the thin Ti-6Al-4V lid, when pushed against the beryllium plate, elastically bends acquiring the same shape of the beryllium surface. In this way, the desired contact pressure on the entire interface between the two parts is ensured [4]. The three prototypes are being examined by neutron diffractometry and neutron tomography in dedicated facilities and preliminary results show that in the third prototype there are no gaps at the contact interface, as opposed to the previous two prototypes.

ACCIDENTAL SCENARIO: LOSS OF THERMAL CONTACT

In the Ti-6Al-4V-cladded Pb solution, the contact pressure at the interface is ensured by press-fitting processes. In addition, the thermal expansion of the lead core subjected to the beam power during operation will contribute to increase the contact pressure at the interface and enhance the heat dissipation to the cooling fluid. The design is based on reasonably conservative assumptions of the thermal contact conductance that is possible to obtain during the manufacturing stage, which determines a predicted peak temperature in the lead core of ~150 °C when it operates at the maximum allowed intensity. In addition, an accidental scenario involving loss of contact between lead and Ti-6Al-4V envelope has been studied to assess the robustness of the design under anomalous events such as manufacturing errors and unpredicted permanent deformations due to excessive beam intensity on target. The examined case considers the quite pessimistic event of the onset of a 0.5 mm gap between the lead core and the Ti-6Al-4V layer along the entire circumference. In such a condition, the lead cylinder subjected to the beam-induced heat deposition expands due to the increase of temperature and the absence of cooling, reducing the existing gap. The process continues until the gap is completely filled. At this point, the contact pressure at the titanium-lead interface starts to increase and the lead cylinder starts to be cooled down, until the equilibrium is reached. The purpose of this study is to assess if during this transient stage the peak temperature

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reaches the lead melting point. Due to the strong dependence between the thermal contact conductance (TCC) and the pressure at the interface, coupled thermal and mechanical finite-element analyses have been performed. The first approach consisted in the following iterative procedure:

1. Introduction of an initial hypothesis of the TCC value.
2. Execution of a thermal analysis.
3. Execution of a structural analysis with the temperature output of the previous thermal analysis as boundary condition.
4. Recording of the contact pressure value at the interface as output of the previous structural analysis.
5. Computation, by the theoretical approach described in [10] and [11], of a new TCC value based on the contact pressure at the interface obtained as output of the previous structural analysis.
6. Reiteration of the procedure using the computed TCC value as boundary condition for the thermal analysis.
7. The procedure ends when the TCC converges to a value differing from the previous step by a maximum of 25 W/m^2 K.

The described approach consists of a weak coupling of the thermal and structural aspects, since the two analyses are solved separately. In addition, a second approach consisting of running a fully coupled thermo-mechanical analysis has been performed. Such a process is more accurate but also more resource-intensive. In this analysis, each node of the finite-element model is associated to both thermal (temperature) and structural (displacements) degrees of freedom. Figure 4 shows the resulting temperature distribution at steady state in an axisymmetric model of the target core, as well as the evolution of the peak temperature in the target.

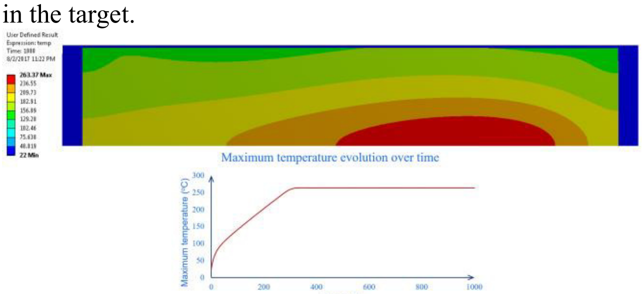

Figure 4. Temperature distribution at steady-state and peak temperature evolution in the accidental scenario (coupled thermo-mechanical analysis).

The maximum temperature reached is about 263 °C, lower than the melting temperature of lead. Therefore, even considering such an accidental scenario, the target design appears to be robust in case of an imperfect or ununiform contact at the interface between lead and titanium alloy.

BEAM IRRADIATION TEST

For both design solutions, real scale prototypes of the target core are being manufactured and will be tested under beam irradiation in the *HiRadMat* facility [12] at CERN. In this facility it is possible to instrument samples with temperature sensors, strain gauges, transducers, etc. and impact them with short 440 GeV proton beam pulses (up to 3.8×10^{13} protons per pulse in 7.6 μs) extracted from the *Super Proton Synchrotron* (SPS) ring. The objectives of the experiment are:

- Validate the target design.
- Assess the capability of the cladding layers to keep their integrity even in case of damage of the contained materials.
- Verify that the target keeps the desired behaviour even after many load cycles.
- Verify the efficiency of the thermal contact at the interfaces between core materials and cladding layers.
- Benchmark finite-element analyses and simulations.

Each prototype will be irradiated by a few thousand pulses. The pulse intensity on target will range up to 2×10^{12} protons per pulse for the Ti-Pb target and up to 4×10^{12} protons per pulse for the Ta-W target. Extensive post-irradiation examinations (PIE), including neutron diffractometry and tomography inspections, will be carried out to observe the conditions of the target materials after the experiment (microstructure, damage evolution, etc.). The production of the experimental tank (Figure 5) for the containment of the samples to irradiate is ongoing.

CONCLUSIONS

The design of the new n_TOF target proceeds into the detailed design stage. The prototyping activity carried out led to a design that guarantees the required cooling efficiency and thermal contact between core and cladding layers. Detailed studies of the target behaviour in case of accidental loss of thermal contact have been performed, showing the robustness of the design with respect to this kind of accidental scenarios. The equipment for the HiRadMat beam irradiation test on two target prototypes is under production. The beam test will be take place in August 2018 and a production readiness review will follow in October 2018.

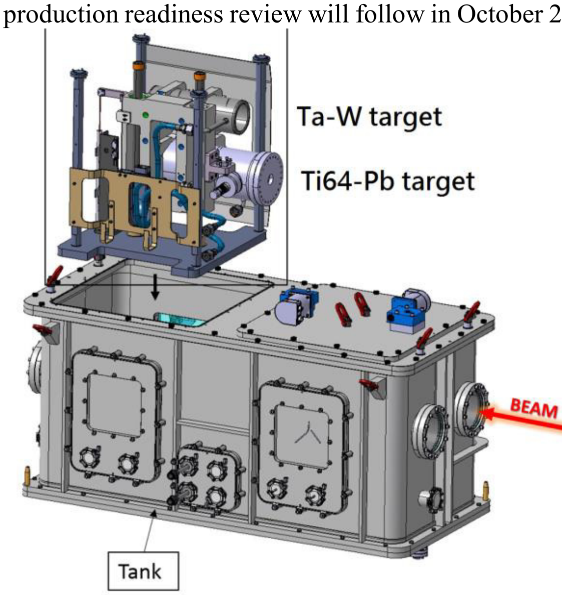

Figure 5. n_TOF HiRadMat experiment tank.

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