Proposal for an air-cooled tungsten spallation target for the n_TOF facility at CERN

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Abstract

A new spallation target for the n_TOF facility at CERN is proposed. The target is based on tungsten and is air cooled. Separate moderators, in the form of removable modules decoupled from the target, can be placed in front of the target for the 185 m station and on top of the target for a future vertical 20 m station.

1 Introduction

After the successful completion of the first phase of the experimental programme of the n_TOF facility at CERN [1], an extension of the experimental programme for the period 2006-2010, under the name as n_TOF-Ph2, has been proposed to the ISOLDE and Neutron Time-of-Flight Committee INTC [2] and approved by CERN's Research Board.

A mandatory condition prior to the execution of the second phase n_TOF-Ph2 is the upgrade of the present spallation target. This target, consisting of lead, has been in direct contact with water serving at the same time as a coolant and a moderator during phase I. The lead target, which is uncladded, needs to be replaced by a new cladded spallation target.

At the time of the start of the first phase of n_TOF the choice of a lead target was obvious because of its availability from the TARC experiment. However, the advantages from the physics point of view of more dense materials like tungsten or tantalum were recognized.

Table 1: Relevant properties of three metals from ref. [3].

material	density (g/cm^3)	melting point °C	thermal conductivity (W/m/K)
lead (Pb)	11.34	327.5	33.0
tungsten (W)	19.3	3370.0	163.3
tantalum (Ta)	16.65	2996.0	54.4

The main advantage of tungsten or tantalum is that these materials have a higher density than lead and therefore the same number of neutrons can be produced by spallation with a smaller volume of material. Table 1 summarizes the main relevant properties. The much higher melting points of tungsten and tantalum as compared to lead allow to have a target cooling which is much less critical concerning heating aspects. Cooling with air instead of water becomes an option.

In the case of air cooling, a separate moderator can be implemented as a replaceable device. The decoupling of the coolant and moderator allows a much more flexible adjustment of the neutron flux of the facility. One could more easily adapt the characteristics of the neutron flux by choosing an appropriate moderator, based on water, heavy water, a cryogenic moderator, or no moderator. Also the 185 m station and the 20 m could have each a different moderator.

A non-negligible advantage is also that avoiding the 900 l of coolant water as in the present target, presents a considerable reduction of liquid nuclear waste related to the operation of the n_TOF facility.

In addition, the smaller target volume for the same neutron flux will significantly improve the energy resolution function. This resolution has a higly asymmetric distribution. Although the full width at half the maximum of the resolution function is largely determined by the thickness of moderator layer, the tail of the resolution is determined by the size of the target. This tail becomes more pronounced at higher neutron energies. A smaller tail will reduce the effect of smearing out resolved resonances, especially at higher neutron energies.

The present situation would be an ideal occasion to consider a new target based on a different material. A project of having a second flight station located vertically at 20 m is currently considered for a third phase beyond 2010. The target should be constructed in such a way that such a second flight path could be constructed with the new spallation target.

2 Preliminary design

Comparing the numbers in table 1 indicates that tungsten would be the most natural choice because it has the highest density. Unfortunately tungsten becomes brittle under

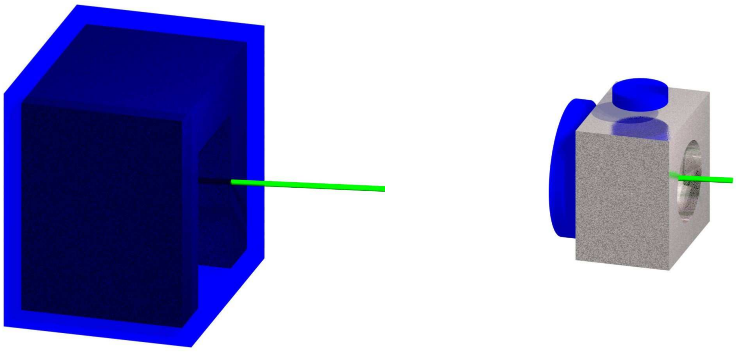

Figure 1: View of the current lead target surrounded by the water coolant and moderator in the left panel, and the preliminary design of a new tungsten air-cooled spallation target in the right panel. Two modular moderators, one for the 185 m station and one for the future 20 m station, shown in blue, are decoupled from the spallation target. Each moderator can consist of water or heavy water contained in aluminum. A flow of air is sufficient to maintain a reasonable surface temperature. The proton beam is visualized by the green cylinder.

irradiation. This can be encountered by using a tantalum cladding around the tungsten target. Tantalum-cladded tungsten spallation targets have been described in two recent studies [4, 5] in a configuration with a much higher power dissipation in the spallation target. At ISIS at Rutherford Appleton Laboratory such a target has been used already and a new one is under design. And also at MTS at LANSCE design studies of tungsten targets are ongoing.

In a first approximation we have used the dimensions of the present lead target, approximately scaled down by the ratio of the densities. The tungsten target will have outer dimensions $50 \times 50 \times 35$ cm^3, as compared to the present lead target with outer dimensions $80 \times 80 \times 60$ cm^3. A view of the two targets is given in figure 1 on the same scale.

The tungsten target has a cylindrical hole on the proton entry side, with 20 cm diameter and 10 cm deep, centered in the middle of the target. The proton beam makes an angle on the incoming side of 10 degrees with the symmetry axis of the target in the horizontal plane. The first moderator for the 185 m station, is 5 cm thick and has a diameter of 25 cm. There is a spacing of 5 cm between the moderator and the target. The second moderator for the future vertical 20 m station, spaced of 5 cm on top of the target, has a diameter of 10 cm and a thickness of 5 cm. Its center is shifted by 3 cm to follow the proton beam.

In the following a comparison between the old and the proposed targets in terms of neutron performances will be given. The cooling aspects will be described after. For the neutron flux calculations the cladding of tantalum has been neglected. For the cooling calculation, the tantalum had to be taken into account because of its lower thermal conductivity.

3 Neutron and gamma flux comparison

3.1 Simulation tools

In order to simulate the neutron flux obtained by proton-induced spallation in a lead and in a tungsten target we have used the Monte Carlo code MCNPX [7]. Both target systems were simulated and compared under the same conditions.

To simulate the n_TOF neutron source consisting of a proton beam of 20 GeV impinging on a lead target, it was necessary to use a non standard version of the MCNPX code featuring the transport of high energy hadrons and fragments and the simulation nuclear reaction mechanisms up to a few tens of GeV. The MCNPX version used is the 25HI7.

The simulations were performed using the LAQGSM model. This model uses the pree-quilibrium and evaporation physics from the CEM2k model and has a number of improvements and refinements in the cascade and Fermi break-up models. Both CEM2k and LAQGSM are able to describe fission reactions and production of light fragments heavier than 4He (using the Generalized Evaporation Model code). This features permit to describe quite well a large variety of spallation, fission and fragmentation reactions at energies from 10 MeV to 800 GeV/c [8].

3.2 The tungsten and the lead target system

The lead target geometry and materials implemented in MCNPX, consists is the same description used in previous simulations of the n_TOF neutron and gamma flux using the FLUKA code. The lead target consists of a 80 x 80 x 60 cm^3 volume submerged in water that works both as a cooling material and as a moderator to shape the neutron flux exiting the target.

The tungsten target as specified above, consists of a 50 x 50 x 35 cm^3 volume, a scaled down version of the previously mentioned lead target. The 5 cm of water in front of the target was kept unchanged. Also, the 2 cm of water surrounding the other faces of the tungsten block used for cooling was kept. The thickness of the Antico container is maintained and the gap between the proton beam line and tungsten target is the same as the one used in the lead target. The dimensions of the I-BEAMS and the aluminum window have been adjusted to fit the new Antico container dimensions. Both targets are represented in figure 2.

The neutron and gamma flux were tallied outside the aluminum window. Conditions

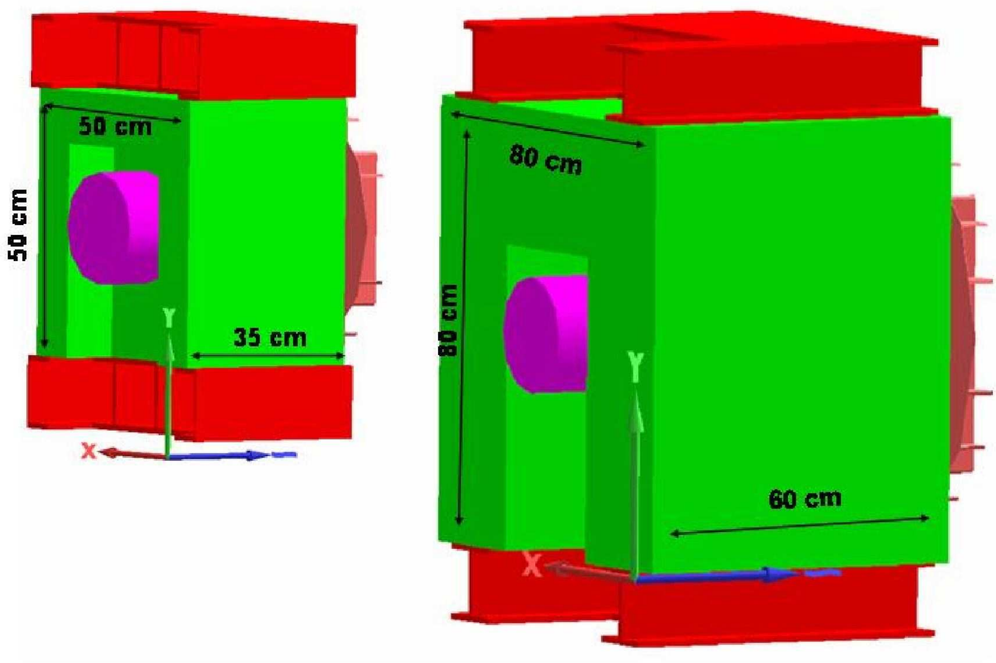

Figure 2: The modelizations of the lead target on the right and the tungsten target on the left on the same scale.

on the exiting angle of the particles were applied. The spectra shown in figure 3 and figure 4 are obtained for particles exiting the aluminum window with a polar angle below 10°relative to the axis of the n_TOF beam line. It must be recalled that only neutrons exiting the target with an angle below 1 mrad relative to the n_TOF beams line will reach the experimental area. However, tallying such particles would require an unrealistic simulation time, in order to obtain accurate results. We believe that tallying all exiting neutrons with angles smaller than 10°is an acceptable solution for obtaining a reasonable statistics and having a good approximation to the real flux shape at the very low angles previously mentioned. The proton incident direction makes 10°in respect to the normal of the n_TOF beam line respecting the real setup conditions.

3.3 Comparison neutron and gamma flux existing Pb and proposed W target for the 185 m station

The neutron flux simulated for both target materials is plotted in figure 3 in isolethargic units normalized by incident proton.

From figure 3 it is possible to see that the neutron fluence is almost a factor 2 higher for the tungsten target in the energy range of relevance for the n_TOF experiments.

The energy spectra (in isolethargic units per incident proton on target) of the photons

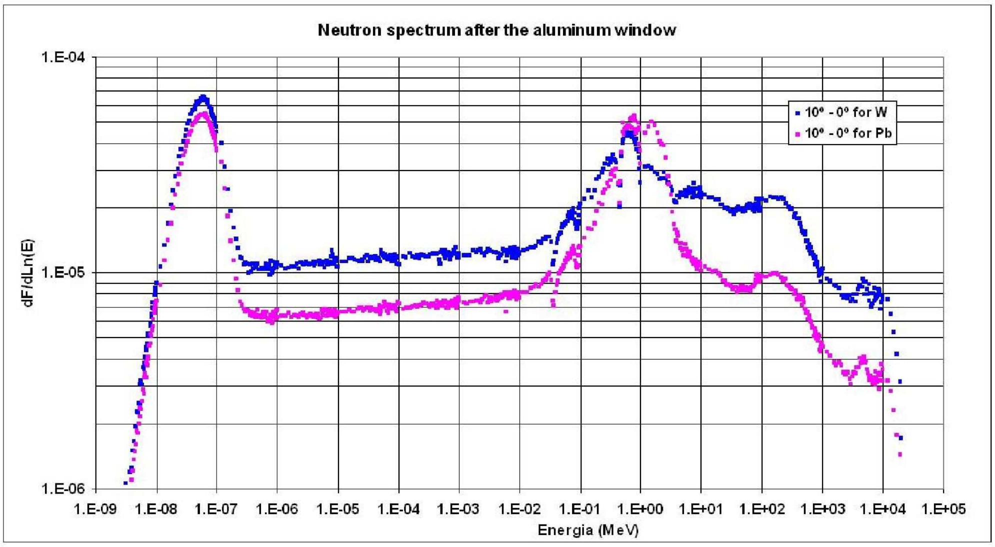

Figure 3: The simulated neutron spectra in the forward direction for the tungsten and lead targets.

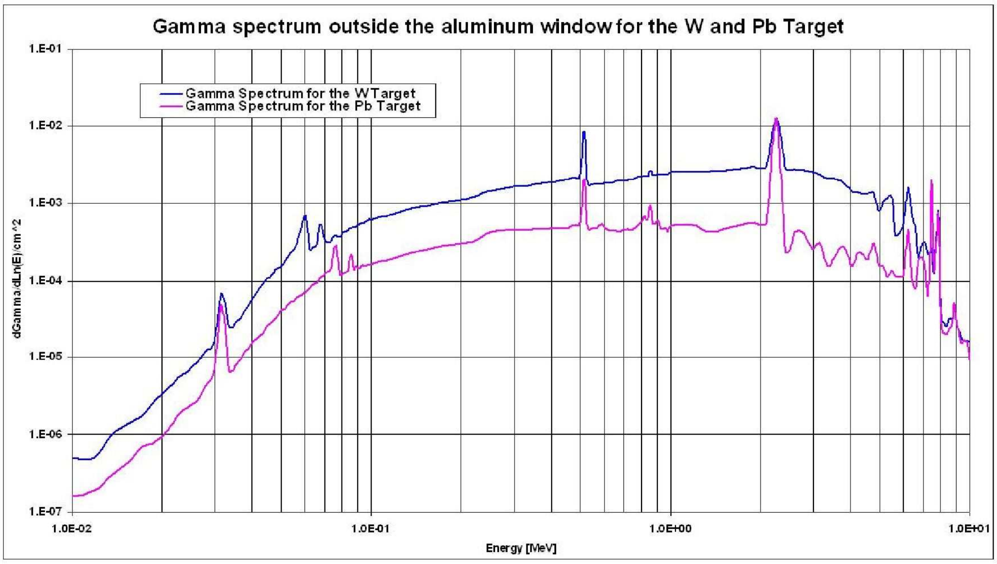

Figure 4: The simulated gamma spectra in the forward direction for the tungsten and lead targets.

exiting the target and crossing the Aluminum window are plotted in figure 4 for both targets. As can be seen from figure 4, the tungsten target originates a much higher photon flux in the energy range of interest.

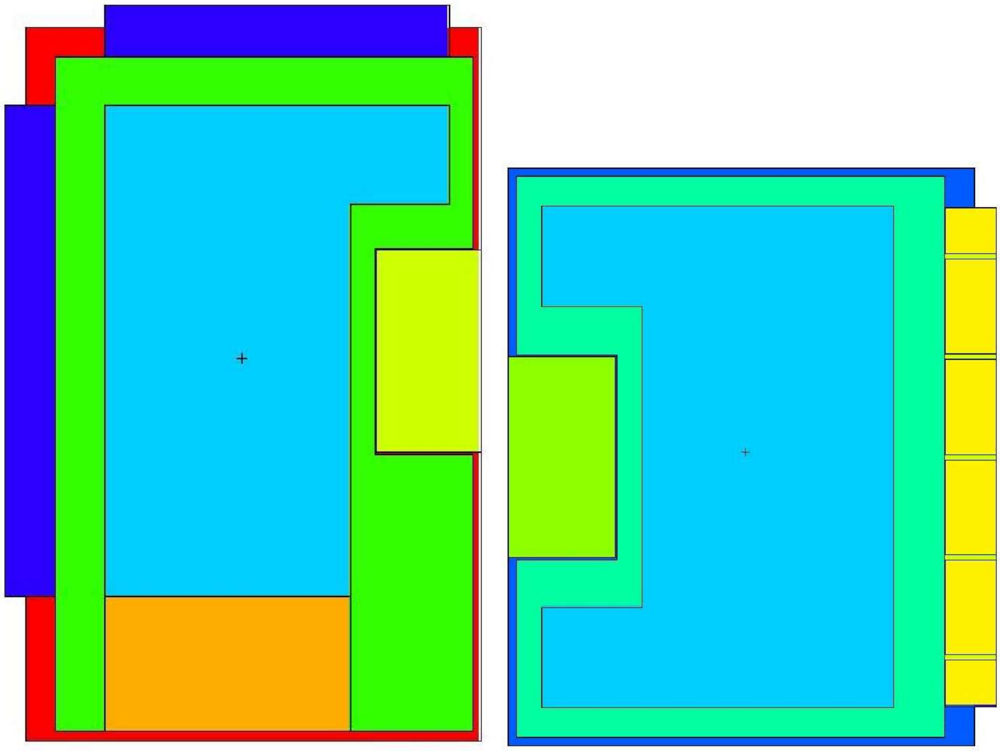

Figure 5: Modified W target to allow two measuring stations. From left to right, vertical cut showing the two aluminum windows (blue) and horizontal cut showing the aluminum window structure (yellow).

3.4 Expected neutron and gamma flux of the proposed W target at the 20 m station

The tungsten target described above was modified to accommodate a second neutron exiting window on the top as shown in figure 5. The I-BEAM on the top of the tungsten target was removed and the Antico container dimensions have been adjusted on the top to allow a 5 cm thickness of water for moderation. The air inside the container was removed. The top window follows the geometry of the front window. All other aspects were unchanged.

Figure 6 shows that the inclusion of a second neutron exit window in the target system will not alter in a noticeable way the neutron flux in the 185 m measuring station.

Figure 7 shows the gamma spectrum for the tungsten target system in comparison with gamma spectra obtained with the modified tungsten target in both windows. It is possible to see that the gamma background on the windows serving the 20 m measuring station is much smaller.

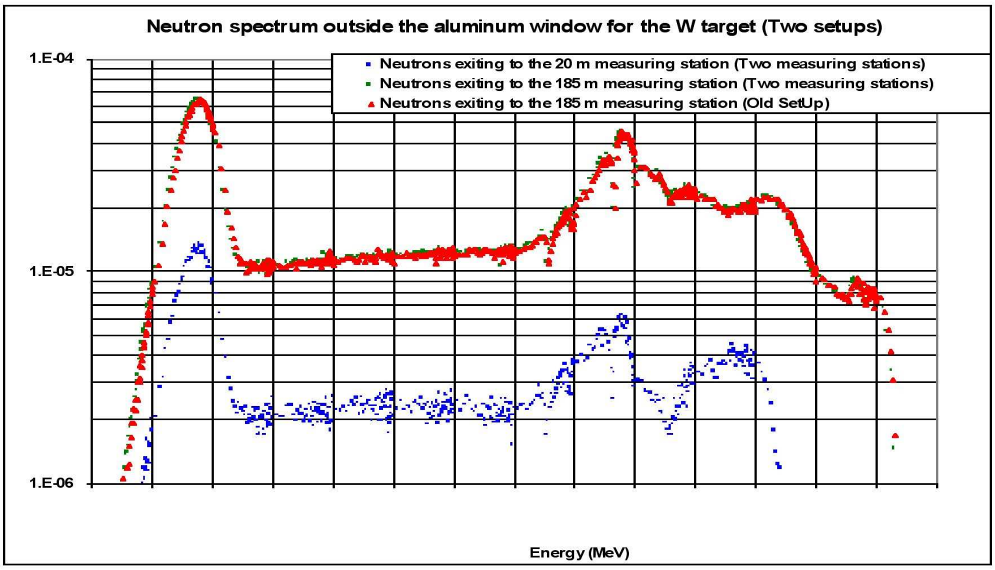

Figure 6: Neutron spectrum for the 185 m measuring station with the tungsten target (red). Neutron spectrum for the 185 m measuring station with the tungsten target modified by an insertion of a second neutron exiting window in the vertical direction (green). Neutron spectrum for the 20 m measuring station with the tungsten target modified (blue).

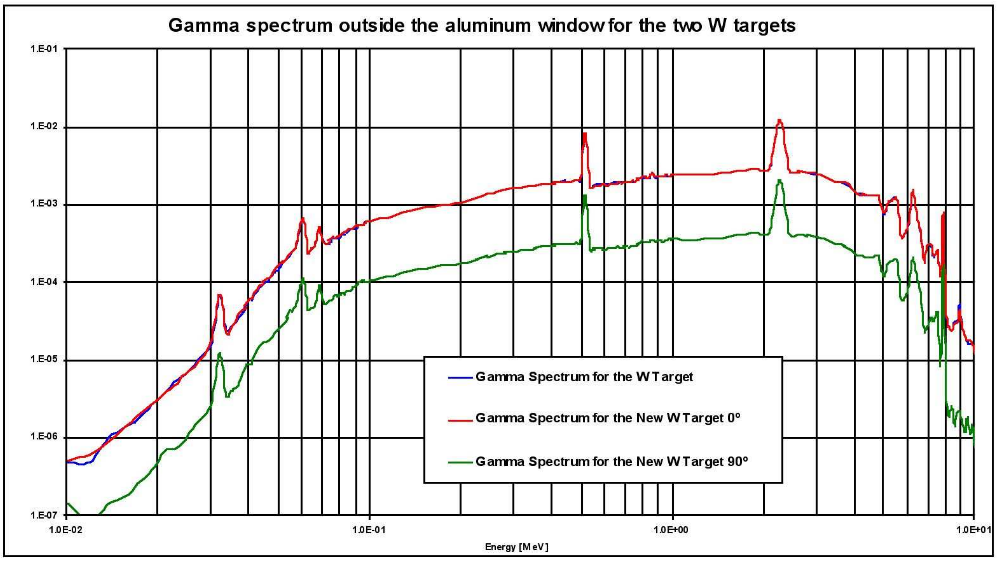

Figure 7: Comparison of the gamma spectra for the two tungsten target setups.

4 Cooling aspects

From the simulations with MCNPX described before, a total heat deposit of 7.1×10^{-10} J per incident proton is expected in the tungsten target. Assuming a number of 7×10^{12} protons/bunch and 5 bunches per supercycle of 16.8 s, this means an average power dissipation of 1.5 kW in the tungsten target. The power dissipation in the water moderator for the 185 m station is only 46 W, and the dissipation in the moderator for the 20 m station is negligeable.

In order to calculate the cooling requirements, we assumed a homogeneous power dissipation in a cylinder of 1 cm diameter following the proton beam through the target. A similar approach of averaging the power dissipation has already been employed for the existing lead target [6] and has been proved to give an excellent conservative estimation compared to the real irradiation conditions.

The geometry has been modelled in the finite element code CAST3M [9], and the thermal equilibrium has been calculated [10]. Details of the calculations are availabe in a separate document. The results are based on the target placed in a 60 cm diameter cylindrical air flow from one side. Due to the excellent heat conductivity of tungsten and tantalum, the temperature in the target is nearly the same in the center and at the surface. A heat exchange coefficient of 45 W/m^2/°C is necessary to keep the target temparature below 93°C. This can be achieved with air of 25 °C and a speed of 17 m/s. If a speed of air of 1.5 m/s is used, comparable to a home-type ventilator, the temperature of the target is about 325°C. Although these numbers are conservative estimates, it is clear that the temperature stays well below the melting temperature of tungsten or tantalum.

If the target is constructed not as a single block, but as 16 2 cm thick tungsten layers covered with 0.2 mm tantalum, and a spacing of 1 mm between each layer, the cooling becomes even more efficient. A heat exchange coefficient of 8 W/m^2/°C is needed to maintain the target temperature below 90°C, implying a speed of air of 1.5 m/s.

Conclusion

A spallation target based on tungsten and cladded with tantalum can be air-cooled and allows the use of a removable moderator. The here proposed tungsten target will have a comparable though higher neutron flux than the lead target used in phase I.

From the experimental point of view the new tungsten target presents several advantages and would make the n_TOF facility even more competitive by combining a high neutron flux and a high resolution. However, practical issues have to be considered.

An estimation of the costs has to be established for the construction, operation and disposal of such a target. Also a study of the change of the cooling system from water to air cooling has to be taken into account. If the lead of the present target cannot be reused for a new cladded lead target, the solution of the tungsten target becomes an interesting alternative.

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