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THIRD-GENERATION CERN n_TOF SPALLATION TARGET: FINAL DESIGN AND EXAMINATIONS OF IRRADIATED PROTOTYPE

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Abstract

The new neutron spallation target for the CERN neutron Time-Of-Flight (n_TOF) facility is based on a nitrogen-cooled Pb core impacted by short high-intensity proton beam pulses. An extensive material characterization campaign has been carried out to define the constitutive behavior of lead and assess its response under pulsed proton beam irradiation. The activities carried out include a beam irradiation test in the CERN HiRadMat facility. The tests and inspections performed show a robust behavior of the core material during operation and prominent static hardening recovery already at room temperature.

THE NEW N_TOF TARGET

The neutron Time-Of-Flight (n_TOF) facility at CERN provides high-intensity pulsed white-spectrum neutrons spanning almost 11 orders of magnitude, from thermal up to several GeV [1-4]. It is composed of a Pb target coupled to two neutron flight paths, and it is driven by a pulsed proton beam from the Proton Synchrotron (PS). Up to $8{\times}10^{12}$ protons, with a momentum of 20 GeV/c and bunch length of 7 ns, are extracted from the PS in a single pulse and impact the target. The initially fast neutron spectrum is moderated by water before being collimated and transported to two Experimental AReas: EAR1, located 185 m downstream of the spallation target, and EAR2, 20 m above the target [3-5]. After the second-generation target reached the end of its design lifetime (10 years), a new target has been manufactured and installed during the CERN Long Shutdown 2 (LS2). The spallation target has been designed considering a maximum number of protons per pulse of 10^{13}, equivalent to a pulse kinetic energy of 32 kJ. The minimum repetition rate is 1.2 s, which determined an average power on target of 6.4 kW. With a pulse duration of 7 ns (RMS), this yields a peak deposited power of 1.5 TW. The beam size on target is assumed to have a radius of 15 mm (RMS). The most severe load case conceivable for the target consists in six pulses every 1.2 s followed by 30 s of cool-down, for a supercycle duration totaling 36 s (Fig. 1).

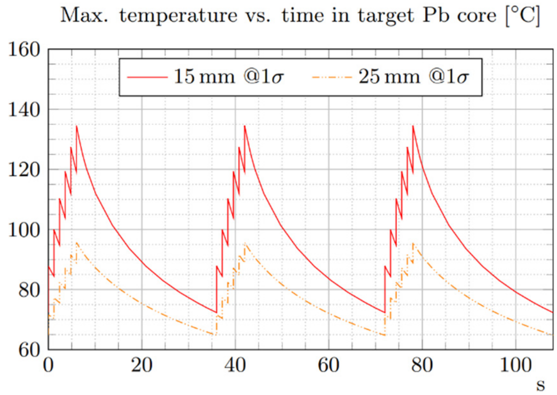

Figure 1: Maximum temperature (estimated by FEM simulations) in the target core during three 36-s supercycles once periodic regime is reached, with beam size radius of 15 mm and 25 mm (1σ).

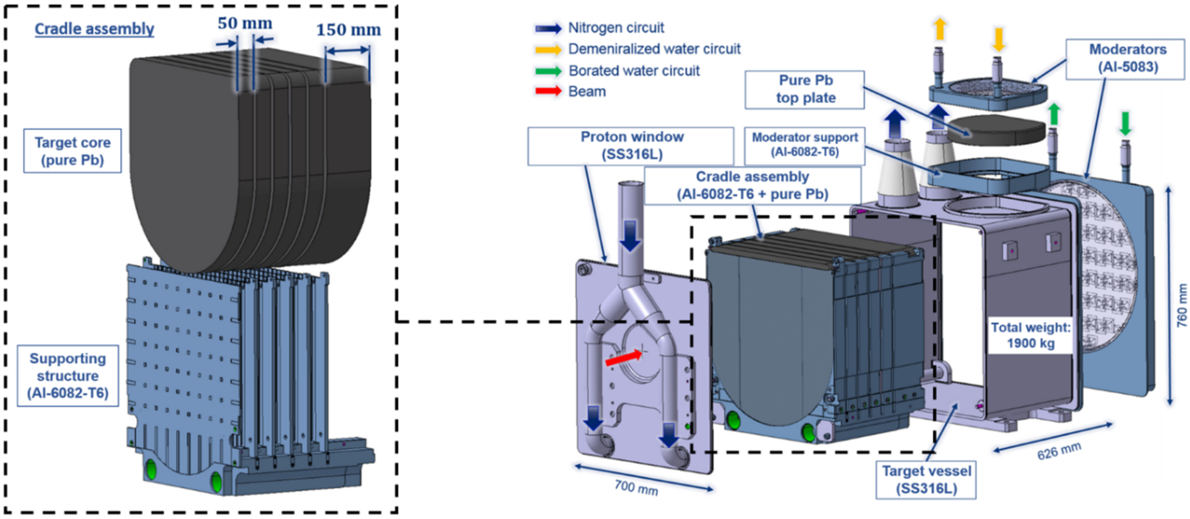

Figure 2: Exploded view of the third-generation neutron spallation target for the CERN n_TOF Facility [6].

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The new target is made of six 60×60 cm^2 pure lead slices, five of which are 5-cm thick while the last slice along the beam direction is 15-cm thick (Fig. 2). The flat top helps improving the resolution function for measurements performed in EAR2 [6]. The lead slices are cooled by a forced flow of pure nitrogen and are supported by an Al-6082-T6 structure. This core assembly is hosted inside a low-cobalt stainless-steel 316 L vessel. Two Al-5083-H112 moderator vessels (to be filled with demineralized water and 1.28 wt% borated water) are equipping the target, one for each experimental area: the EAR2 moderator is mounted outside of the vessel, above the target, while the EAR1 moderator is integrated into it and represents its downstream face. The bond between the EAR1 moderator and the stainless-steel vessel is realized by explosion bonding. An extensive validation campaign has been carried out on the explosion-cladded joint (Fig. 3).

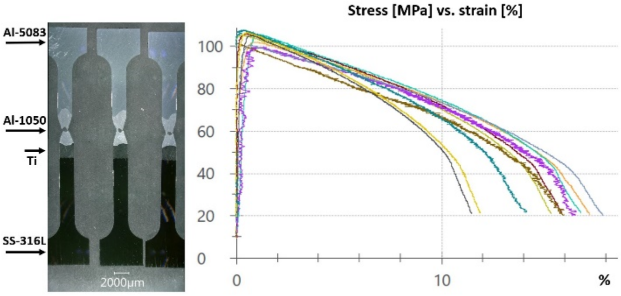

Figure 1: Tensile tests on the explosion-bonded transition. The joint strength is not lower than the one of the weakest material, Al-1050 (commercially pure aluminum).

In 2021, the target manufacturing and assembly has been concluded (Fig. 4) and the target has been installed in the beamline.

Figure 2: Third-generation n_TOF target before installation in the beamline.

BEAM IRRADIATION EXPERIMENT

The most critical aspect of the target thermo-mechanical response is related to the impulsive character of the thermal load. This, coupled with the low elastic limit stress of pure lead, induces propagation of plastic stress waves in the core material. The robustness of the lead target when subjected to such intense shocks has been analyzed in [6] and tested with a beam-irradiation experiment in the CERN HiRadMat facility [7]. A reduced-scale prototype of the target has been impacted by 1500 beam pulses with a momentum of 440 GeV/*c*, a beam size of 4 mm (1σ along x and y), and an intensity of 4.5×10^{10} protons per pulse. The beam parameters have been chosen to induce an amount of fatigue damage in the prototype comparable to the one in the target during its entire lifetime. As the target, the prototype consists of six lead blocks in nitrogen atmosphere, but smaller in size (10×10×50 cm^3 for the entire prototype, Fig. 5).

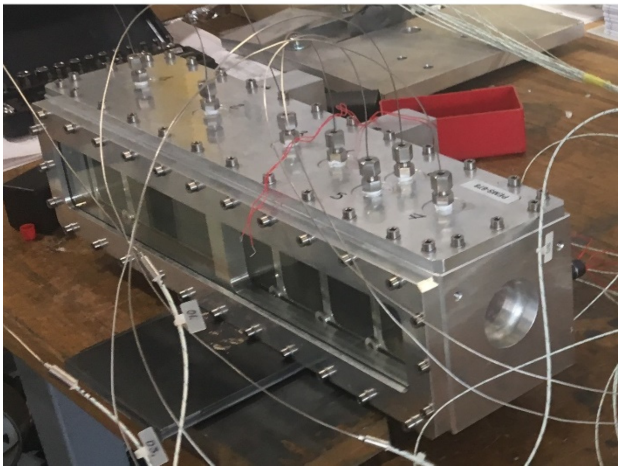

Figure 3: Reduced-scale prototype of the n_TOF third-generation target irradiated in the CERN Hiradmat facility (HRMT-46 experiment).

After the beam-irradiation experiment, the prototype has been inspected to study the effects of the repeated beam impacts (presence of voids, defects, etc.) on the lead blocks, in the temperature range 100-140 °C. The temperature has been monitored and held in the desired range during the test by thermocouples applied to each block and coupled with a series of heating foils in a feedback loop.

An alternative target solution, characterized by a water-cooled pure lead mass protected by a Ti-6Al-4V cladding, has also been prototyped and tested in the HiRadMat facility. Once extracted from its stainless-steel water vessel, it will as well be subjected to similar post-irradiation examinations. Despite the latter being a valid alternative, the nitrogen-cooled bare lead solution has been chosen for its lower complexity and simpler assembly, reducing uncertainties and potential points of failure [5, 6].

POST-IRRADIATION EXAMINATIONS

The lead blocks have been examined by neutron tomography at the Paul Scherrer Institut (PSI, [8]) in Switzerland to detect the onset of damage and voids inside the material. The tomographic examination exposed the inner microstructure and grain boundaries inside the blocks, and no trace of material damage has been detected (Fig. 6).

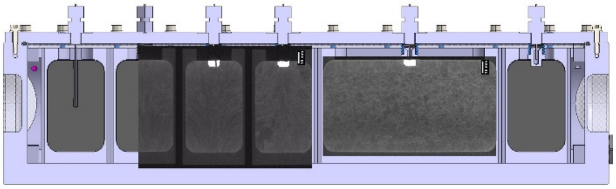

Figure 4: Cross-section of the target prototype tested under beam irradiation in the CERN HiRadMat facility (HRMT-46 experiment). For some lead blocks, one frame from the neutron tomography performed at PSI is shown, revealing the inner microstructure of the blocks and the absence of internal voids. The white areas visible at the top of the blocks are the holes hosting the thermocouples.

In addition, the lead blocks have been subjected to metrological measurements on their external surface. The analysis has shown some permanently deformed zones around the beam impact area. The maximum measured deformation is correlated, in each block, with the energy absorbed in the interaction with the proton beam. The maximum measured deformation is 115 µm in the block with the highest energy deposition.

The external surfaces of the lead blocks have also been subjected to Brinell hardness measurements. The measured values are typical of the unhardened material, even in points where hardening was expected (Fig. 7). This result may be explained by the proclivity of pure lead to phenomena inducing stress relaxation and hardness recovery, such as creep, static recovery, and recrystallization. Such effects are especially relevant, for pure lead, in the temperature range of interest (100-140 °C).

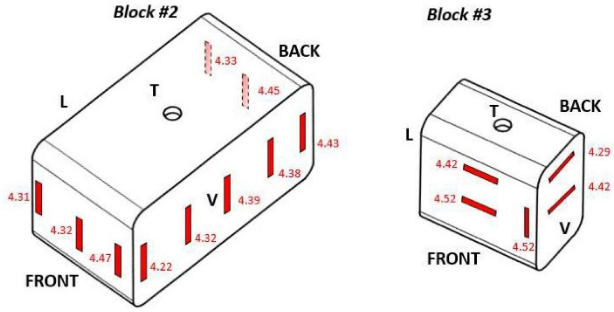

Figure 5: Hardness measurements on the pure lead blocks irradiated in the test under proton beam. The difference in values are not statistically relevant and are typical of the unhardened material.

Uniaxial tests have been performed on pure lead specimens to estimate the extent of these effects. The specimens have been subjected to strain-controlled load cycles followed by a period where the maximum strain is held constant. One example is reported in Fig. 8: the material is cyclically loaded between a strain of 1.5% in tension and in compression, at a strain-rate of 0.1 s^{-1}. The loading pattern is representative of the one the material has undergone in the beam irradiation experiment in the points with the highest accumulated plastic strain. During this loading stage, the material cyclically hardened until a plateau of 15 MPa is reached after 120 cycles. After this stage, the specimen is held in tension at the maximum strain of 1.5% for 20 minutes. The time evolution of the measured stress shown in Fig. 8 reveals how, already at room temperature, the measured stress is almost totally recovered after only 7 minutes. These results may explain the observations resulting from the hardness measurements, since the relaxation effects are expected to be even more relevant in the tested range of temperature (100-140 °C).

The post-irradiation examinations have shown that, despite being a soft material with low resistance to plastic flow, a pure lead target remains the best candidate for the n_TOF spallation source. Besides providing superior physics performance (reduced photon background due to its very low neutron capture cross-sections [5, 6]), it responds well to the high-intensity beam impacts from the PS: while it is sensitive to plastic deformations and creep (requiring it to be supported and contained), it does not develop internal voids, and residual stresses due to thermal shocks are quickly relaxed thanks to recovery and recrystallization phenomena at the operating temperature.

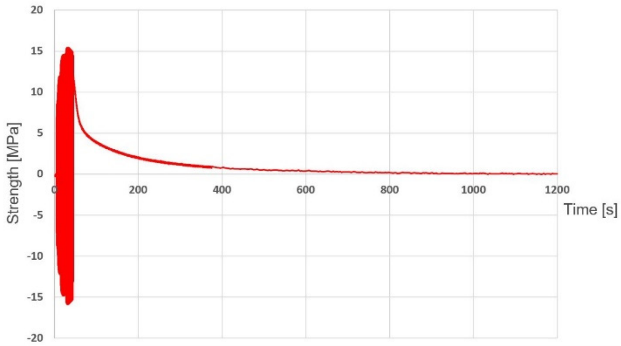

Figure 6: Strain-controlled cyclic tests performed on pure lead specimens: the material is cyclically loaded between a strain of 1.5% in tension and in compression, at a strain-rate of 0.1 s^{-1}, for 120 cycles. The specimen is then held in tension for 20 minutes. The material cyclically hardens until a plateau of 15 MPa is reached, then the measured stress decays while the maximum strain is held constant.

CONCLUSION

The final design of the third-generation neutron spallation target for the neutron Time-Of-Flight facility at CERN (n_TOF) has been presented. A prototype of the target has been tested under beam irradiation in the HiRadMat facility at CERN, validating the target robustness. Post-irradiation examinations, including neutron tomography, did not reveal any internal void or defect. Mechanical tests have shown pronounced stress relaxation effects even at room temperature, confirmed by hardness measurements performed on the irradiated blocks. The target has been installed in the facility in the first half of 2021, and commissioning with beam will start in July 2021.

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