

Design, prototyping, and thermo-mechanical modelling of a neutron spallation target impacted by high-energy proton-beam pulses in the n_TOF facility at CERN

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Abstract

This manuscript describes the design work and the R&D activities carried out for the third-generation neutron production target in the neutron Time-Of-Flight (n_TOF) facility at the European Laboratory for Particle Physics (CERN). The facility is composed of a neutron source coupled to two flight paths delivering a white-spectrum, pulsed neutron beam to two experimental areas. The neutrons are produced by the spallation reaction induced in lead-based target by a pulsed high-intensity proton beam with a momentum of 20 GeV/c extracted by the Proton Synchrotron, one of the circular particle accelerators of the CERN complex. The impact of high-energy proton beam pulses induces severe thermo-mechanical loads on the target, posing challenges for the target design.

A description of the design process is provided, which started with the examination of multiple potential target concepts by means of numerical codes aimed to find a design offering an optimal combination of physics performance and thermo-mechanical response. The process converges towards a final design based on a series of pure-lead blocks supported by an anti-creep structure in aluminum alloy and cooled by nitrogen gas. Novel approaches to simulate material response are presented and degraded operational scenarios are analyzed.

The execution of two beam irradiation tests on target prototypes in a dedicated CERN facility is described, followed by post-irradiation examinations including neutron tomography inspections.

The manuscript ends presenting the results of cyclic mechanical characterization tests on pure lead at different temperatures and strain-rates, and the proposal of a new constitutive model to better simulate the evolution of the material behaviour when subjected to repeated impacts of proton beam pulses.

Keywords: CERN, n_TOF, neutron, time of flight, target, lead, Pb, constitutive, HiRadMat, beam irradiation test.

Résumé

Ce manuscrit décrit les études de conception et les activités de recherche réalisées pour une nouvelle cible de production de neutrons, dans l'installation *neutron Time of Flight* (n_TOF) du Laboratoire européen pour la physique des particules (CERN). L'installation est composée d'une source de neutrons couplée à deux lignes de faisceau délivrant un spectre blanc des neutrons pulsés vers deux zones expérimentales. Les neutrons sont produits par la réaction de spallation induite dans une cible en plomb par un faisceau de protons pulsé de haute intensité à 20 GeV/c, extrait par le *Proton Synchrotron*, l'un des accélérateurs de particules du CERN. L'impact du faisceau de protons à haute énergie induit des contraintes thermomécaniques élevées sur la cible, ce qui pose des défis pour sa conception.

Une description est donnée du processus de conception et de l'évaluation de différentes solutions de conception à l'aide de modèles numériques visant à trouver le compromis optimal entre performance et réponse thermomécanique. Le processus converge vers un design final basé sur une série de blocs de plomb pur supportés par une structure anti-fluage en alliage d'aluminium et refroidis par de l'azote gazeux. De nouvelles approches pour simuler la réponse des matériaux sont présentées et des scénarios opérationnels dégradés sont analysés. L'exécution de deux tests d'irradiation par faisceau sur des prototypes de cibles dans une installation dédiée du CERN est décrite, suivie d'examens post-irradiation comprenant des inspections par tomographie neutronique.

Le manuscrit se termine en présentant les résultats d'essais de caractérisation mécanique cyclique sur du plomb pur à différentes températures et taux de déformation, et la proposition d'un nouveau modèle de comportement pour mieux décrire le comportement du matériau lorsqu'il est soumis à des impacts répétés d'impulsions de faisceau de protons.

Mots-clé: CERN, n_TOF, neutron, time of flight, cible, plomb, Pb, loi de comportement, HiRadMat, test d'irradiation.

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List of Acronyms

AD	Antiproton Decelerator
ADS	Accelerator Driven System
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC Apparatus
BROND	Russian Recommended Evaluated Neutron Data Library
CAD	Computer-Aided Design
CENDL	Chinese Evaluated Nuclear Data Library
CERN	European Laboratory for Particle Physics
CFD	Computational Fluid Dynamics
CHT	Conjugate Heat Transfer
CMS	Compact Muon Solenoid
EAR1	Experimental Area 1
EAR2	Experimental Area 2
ENDF	Evaluated Nuclear Data File
EPDM	Ethylene Propylene Diene Monomer Rubber
EXFOR	Experimental Nuclear Reaction Data Library
FEM	Finite Element Method
FLUKA	Fluktuierende Kaskade
FWHM	Full Width at Half Maximum
GELINA	Geel Linear Accelerator
HAZ	Heat-Affected Zone
HEPA	High-Efficiency Particulate Air
HIP	Hot Isostatic Pressing
HTC	Heat Transfer Coefficient
IAEA	International Atomic Energy Agency
INFN	Istituto Nazionale di Fisica Nucleare
ISOLDE	Isotope Separator On Line Device
JEFF	Joint Evaluated Fission and Fusion Nuclear Data Library
JENDL	Japanese Evaluated Nuclear Data Library
LANSCE	Los Alamos Neutron Source Center
LHC	Large Hadron Collider

List of Acronyms

LHCb	Large Hadron Collider beauty
Linac4	Linear accelerator 4
LS1	Long Shutdown 1
LS2	Long Shutdown 2
LS3	Long Shutdown 3
LSDS	Lead Slowing Down Spectrometer
n_TOF	neutron Time Of Flight
nELBE	neutron Electron Linac for beams with high Brilliance and low Emittance
NTNU	Norwegian University of Science & Technology
NFS	Neutrons For Science
PIE	Post-Irradiation Examination
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
PSI	Paul Scherrer Institute
R&D	Research and Development
RMS	Root Mean Square
SINQ	Swiss Spallation Neutron Source
SPS	Super Proton Synchrotron
SST	Shear Stress Transport
TCC	Thermal Contact Conductance
TIG	Tungsten Inert Gas
TOF	Time of Flight
UPF	User-Programmable Feature

1 The n_TOF neutron facility at CERN

1.1 The European Laboratory for Particle Physics and its experimental facilities

1.1.1 Introduction

The acronym *CERN* comes from the original French name of the institution, Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research), which is today referred to as European Laboratory for Particle Physics to better describe its current main field of research [1]. CERN is an international organization founded in 1952 and located on the border between France and Switzerland, near Geneva. It has today 23 member states and different association and cooperation agreements with countries and institutions all over the world.

CERN hosts the largest and highest energy particle accelerator in the world, the Large Hadron Collider (LHC). It is a 27-km long circular collider composed of thousands of superconducting magnets driving two proton beams with a energy of 6.5 TeV/ c in opposite directions. The proton beams are eventually collided, at a collision energy of 13 TeV/ c , in four experimental insertions located along the ring (ATLAS, ALICE, CMS, and LHCb). The accelerator ring is installed in a circular tunnel at a depth between 50 and 175 m below ground level.

The LHC is not the only accelerator in the CERN complex, which consists of a chain of five particle accelerators delivering charged particles with increasing kinetic energy. Figure 1.1 shows a schematic of the accelerator complex [2]. A typical physics run starts by accelerating negative hydrogen ions (H^- , consisting of a hydrogen atom with an additional electron) from an ion source to an energy of 160 MeV in a linear accelerator, the Linac4. The hydrogen ions are stripped of their two electrons during injection from the Linac4 into the first ring of the accelerator chain, the Proton Synchrotron Booster (PSB), resulting in a proton beam. The beam is accelerated to 2 GeV in the PSB and injected into the Proton Synchrotron (PS), which in turn brings the proton beam to an energy of 14 GeV/ c and injects it into the Super Proton Synchrotron (SPS), a 7-km circular accelerator. Finally the SPS injects, by two injection lines, two proton beams at 450 GeV/ c in opposite directions into the last ring of the accelerator

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chain, the LHC. In the LHC the two proton beams are accelerated up to 6.5 TeV and collided in four particle detectors at a collision energy of 13 TeV.

The proton beams travel in the LHC in ultra-high vacuum, guided by an electromagnetic field generated by superconducting magnets. The magnets are kept at extremely low temperature (1.9 K) by a cooling system based on liquid helium. Other than protons, heavy ions are also collided in the LHC.

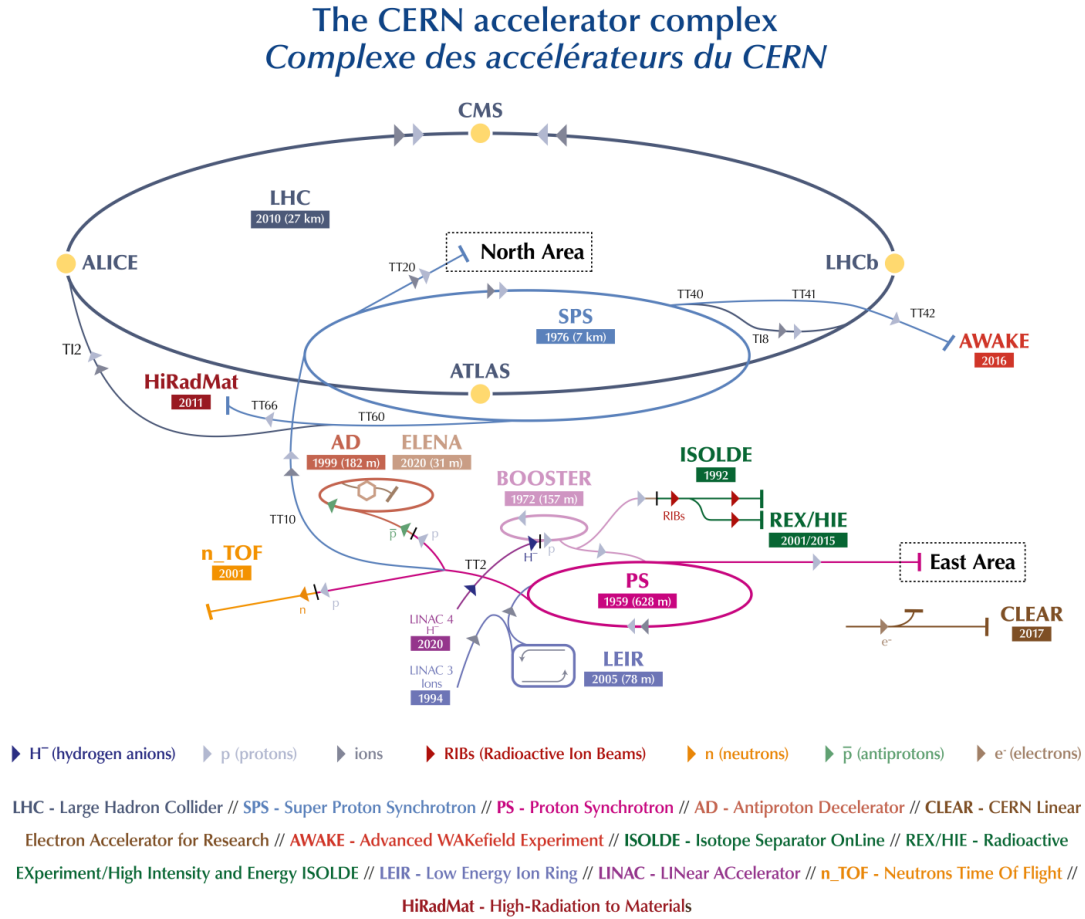


Figure 1.1. The layout of the CERN accelerator complex [2]. In a typical physics run, a chain of five accelerators brings two particle beams to an energy of 6.5 TeV, which are eventually collided at a collision energy of 13 TeV in the four main LHC detectors. In addition to these, many other experimental facilities are installed along the accelerator chain.

1.1.2 The experimental facilities

Less than 0.1% of the protons generated at CERN end up colliding in the LHC [3]. Most of them are used in fixed-target experimental facilities, where the particle beam impacts a fixed target in order to generate secondary or tertiary particles of interest for different experiments.

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The Isotope Separator On Line Device (ISOLDE [4]), for example, is a facility where a 1.4-GeV/ c beam from the PSB interacts with thick targets to produce radioactive nuclides. In the Antiproton Decelerator (AD [5]), a 26-GeV/ c proton beam extracted from the PS impacts thin rods of refractory materials, such as iridium and tantalum, to generate a low-energy beam of antiprotons; the antiprotons are then slowed down to produce and study antimatter. The neutron Time-Of-Flight (n_TOF) facility, which is the subject of this work, is composed of a pure-lead target impacted by a 20-GeV/ c proton beam extracted from the PS; the objective is the production of neutron beams for different experiments (more details will be given in Sec. 1.2).

Figure 1.2 shows a breakdown of the distribution of protons generated at CERN in 2016 [3]. Most of them (61%) do not even reach the PS, since they are delivered to the fixed target experiments in ISOLDE. The n_TOF facility uses about half of the protons extracted from the PS, or 15% of the total amount. The remaining fraction is used in AD and other facilities and experiments at CERN.

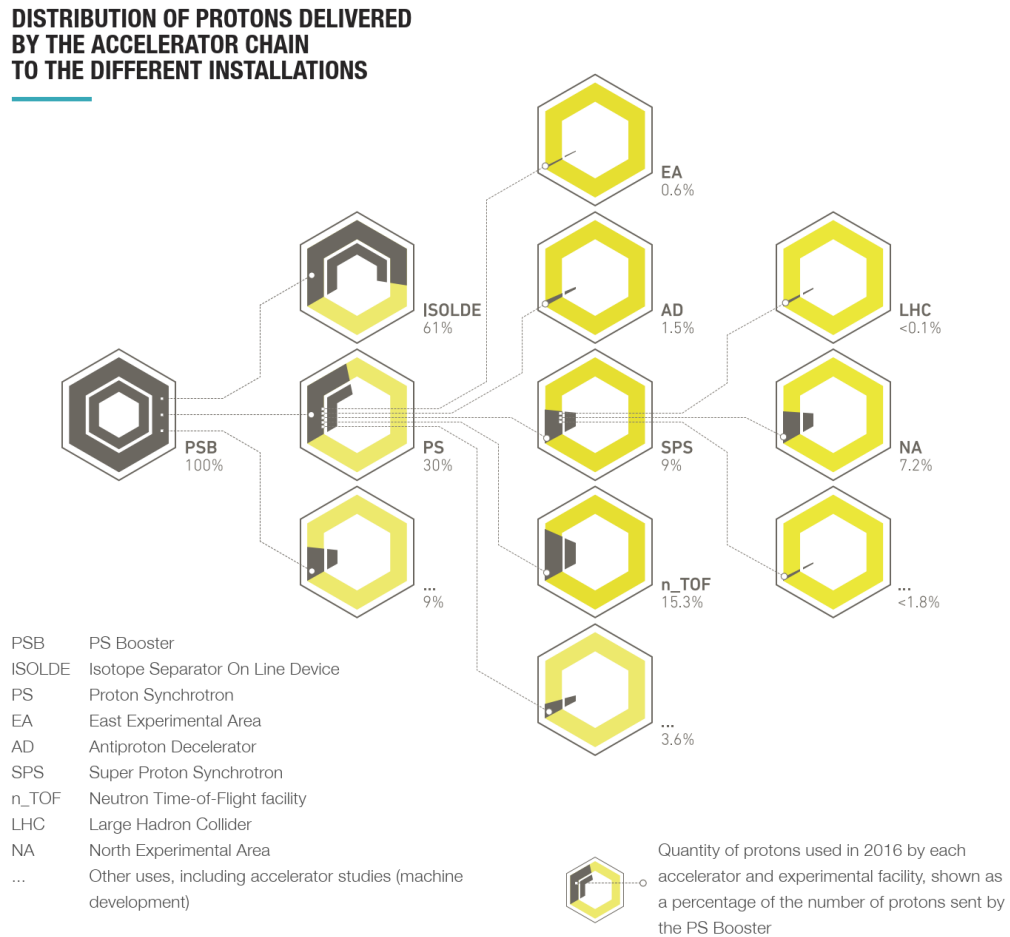


Figure 1.2. Distribution of protons among the experimental facilities at CERN [3]. Most protons generated at CERN are used in fixed-target experiments at ISOLDE, n_TOF, and other facilities. Only a tiny percentage is used for beam-beam collisions in the LHC.

1.1.3 The schedule of CERN activities

CERN activities follow an alternation of two macrocycles: physics *runs* and *long shutdowns*. In the former, the particle beams circulate in the accelerators to run the physics experiments; in the latter, the accelerators are turned off and it is possible to perform major maintenance interventions and machine upgrades. Shorter technical stops also take place during physics run periods, for example at the end of the year.

The first LHC run started in 2008 and ended in 2013 with a maximum collision energy of 8 TeV and the discovery of the notorious Higgs boson, one of the fundamental pieces of the Standard Model theory; the Long Shutdown 1 (LS1) followed and lasted two years, during which the machine was upgraded for collisions at 13 TeV. Run 2 started in 2015 and ended in 2018, followed by the Long Shutdown 2 (LS2). During LS2, most CERN facilities have undergone major upgrades, including n_TOF. The LHC Run 3 will start in 2022, with first low-intensity test beams from September 2021. The smaller accelerator rings and their experimental facilities, like n_TOF, began to receive beam earlier, in spring 2021. According to the current schedule, the third long shutdown (LS3) will start at the end of 2025 and end in 2029.

1.2 The n_TOF facility

1.2.1 The importance of neutron cross-section measurements

A neutron cross-section represents the likelihood of interaction between a neutron and the nucleus of an atom. Evaluations of neutron cross-sections are collected in nuclear data libraries such as JEFF, ENDF, JENDL, CENDL, BROND, and others [6]. Experimental measurements of nuclear cross-sections are also collected in nuclear databases like the Experimental Nuclear Reaction Data Library (EXFOR [7, 8]) managed by the International Atomic Energy Agency (IAEA). Experimental measurements are of fundamental importance for the evaluations, which also take into account nuclear physics models.

An accurate knowledge of this data is of utmost importance in the nuclear technology field as it is strictly necessary for the design, validation, and reliability of nuclear reactors. For example, the energy provided in a nuclear power plant is released from the fission of uranium isotopes due to the collisions of their nuclei with impinging neutrons; in this interaction, the neutron cross-section covers a fundamental role as it is necessary to compute the *reaction rate*: number of fission reactions per unit of reactor core volume and unit of time. If the energy released per each fission is known, it is then possible to compute also the rate of energy released in the reactor [9].

Along with the computation of these and many other parameters of interest for the design of nuclear reactors, an accurate knowledge of neutron cross-sections covers a fundamental role not only for traditional nuclear power plants, but also for research in novel concepts of nuclear technology, such as nuclear power plants based on the thorium fuel cycle, transmutation of

nuclear waste, Accelerator-Driven Systems (ADS), and Generation-IV nuclear reactors [10].

Moreover, the knowledge of neutron cross-sections is not only important for nuclear technology and fundamental knowledge in nuclear physics, but also for other fields like cosmology (origin of chemical elements in stars), radiation dosimetry, and radioisotope activation for medical applications [11, 12].

1.2.2 The facility

Driven by the reasons mentioned in Sec. 1.2.1, the international n_TOF Collaboration was formed with the objective of developing a new neutron source dedicated to accurate neutron cross-section measurements and characterized by a white spectrum in a wide energy range, high neutron flux, high resolution, and low photon background.

Being located at CERN, the facility has taken advantage of the preexisting high-energy proton source, the Proton Synchrotron. A proton beam with a momentum of $20\text{-GeV}/c$ is extracted from the PS (Fig. 1.1, 1.3, and 1.4) and impacts a pure-lead target. The interaction between proton beam and target produces neutrons via the *spallation* mechanism (see Sec. 1.2.3).

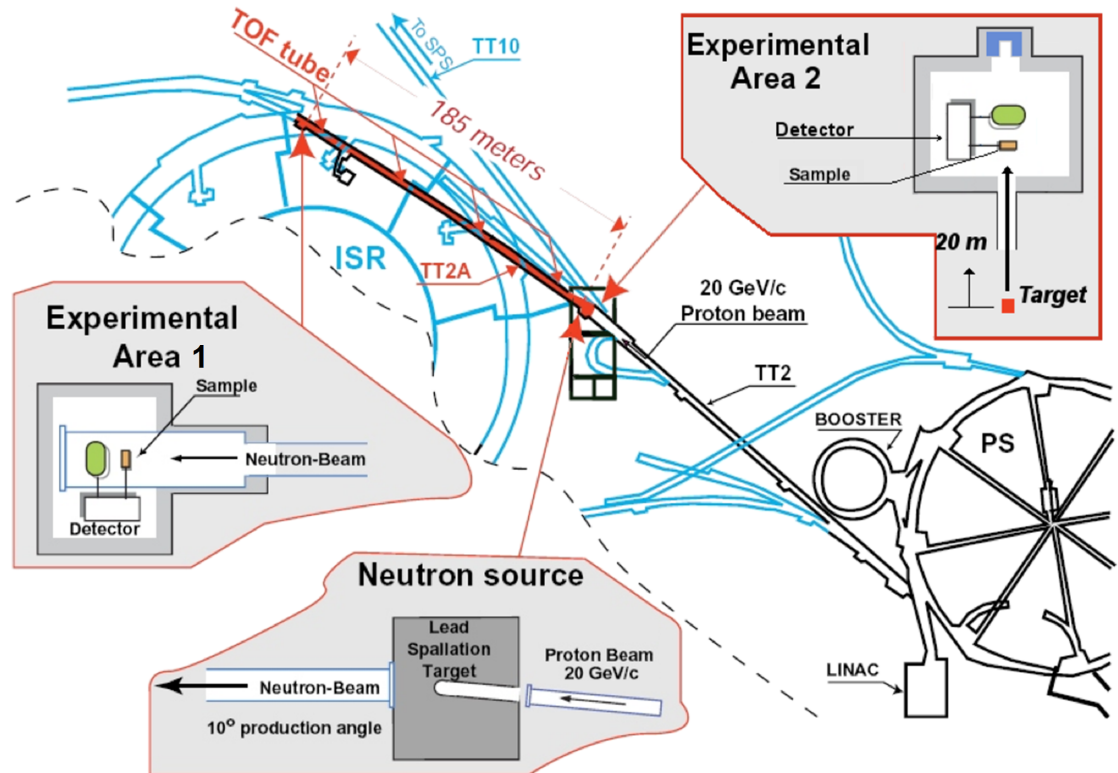


Figure 1.3. The layout of the n_TOF facility (from [13]). The PS accelerator at CERN delivers a $20\text{ GeV}/c$ beam to a pure-lead target. The neutrons produced are detected in two experimental areas: EAR1, at 185 m from the target, and EAR2, 20 m above the target.

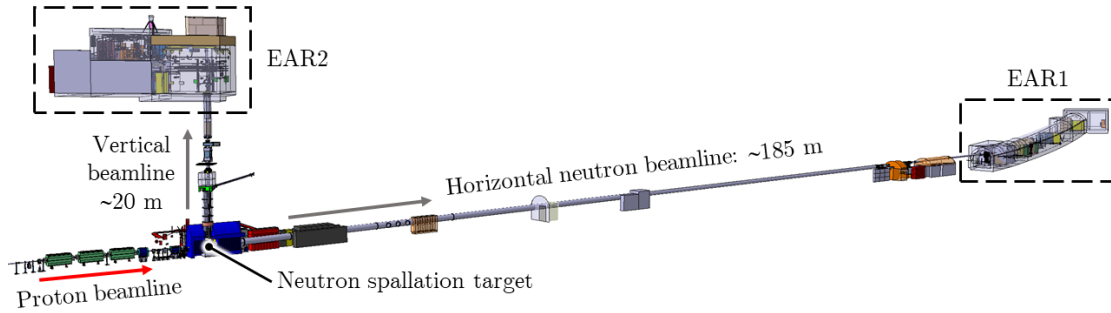


Figure 1.4. A 3D-model overview of the CERN's n_TOF facility.

The initially fast and highly-energetic neutrons are slowed down (moderated) by two water moderators, after which they continue travelling toward two experimental areas: the Experimental Area 1 (EAR1) is located 185 m from the target, while the Experimental Area 2 (EAR2) is located 20 m above the target (Fig. 1.3 and 1.4). The two experimental areas are equipped with detectors for neutron-induced reaction measurements via the time-of-flight method, hence the name of the facility.

The time-of-flight method consists in the computation of the neutron kinetic energy via the measurement of the time interval between the production of neutrons at the target and the detection of their interaction with a sample in the experimental area.

1.2.3 The spallation mechanism for neutron production

The spallation mechanism takes place when high-energy nucleons or light nuclei (typically above some hundreds of MeV) interact with the heavy nuclei of a massive target. In this first stage, called *intra-nuclear cascade*, the high-energy projectiles knock out some nucleons (and light nuclei) from the target nuclei and leave them in an excited state. The excited residual nuclei undergo a process of deexcitation through high-energy fissions and a stage called *evaporation*, where more nucleons (mostly neutrons) leave the target nuclei. In the final stage, further low-energy inelastic and elastic reactions take place [10].

Spallation as neutron production mechanism is the natural choice when a preexisting high-energy proton beam source like the PS is available, thanks to the high neutron yield per impinging proton (up to 300 n/p⁺ in n_TOF [14]). The amount and energy of the generated neutrons depends mostly on the type and energy of the impinging beam and target material. The graph in Fig. 1.5 shows the yield of spallation neutrons depending on the impinging proton beam energy, for thin targets made of different materials: the neutron yield grows with the proton energy, beginning to saturate at around 2 GeV. Heavier target materials, such as actinides, are able to produce more neutrons; these materials are characterized, though, by a much higher radioactivity of the target since they are subject to fission reactions. The main advantages of lead as spallation material are its high neutron yield and the high transparency for neutrons at energies lower than 1 MeV. A uranium target could offer a higher neutron yield

but it would be subject to a much higher activation and introduce considerable complications with regard to safety requirements.

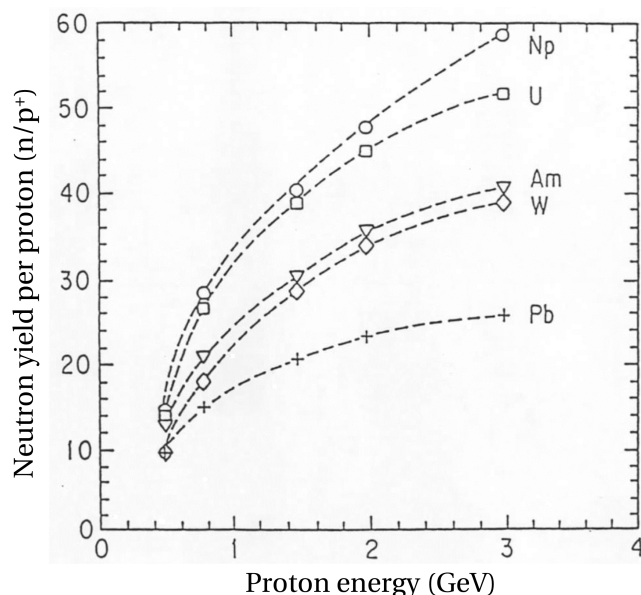


Figure 1.5. Neutron yield by spallation vs. impinging proton energy for different thin targets [15]. Some materials, such as actinides, can yield more neutrons per impinging proton; they are characterized, though, by a much higher target radioactivity due to fission reactions.

Along with neutrons, many other secondary particles are produced in the spallation process, such as muons, protons, and pions. High-energy particles other than neutrons can pollute the neutron beam and reduce the quality of the measurements. Since most of these particles are emitted in the same direction of the impinging proton beam, this contamination is lower if there is a certain angle between the impinging proton beam and the neutron beamline. This is the case for n_TOF, where the proton beam is not parallel to the horizontal neutron flight path, but hits the target forming an angle of 10° in the horizontal plane (see Fig. 1.3).

1.2.4 The neutron moderation

The initially high-energy neutrons generated in the nuclear cascade are slowed down (moderated) before leaving the target area by two water moderators, one for each experimental area. Thanks to them, the neutron beam covers about eleven orders of magnitude in energy, from several GeV to subthermal energies (thermal neutrons are neutrons in thermal equilibrium with their surroundings). Without moderation, the neutrons would mostly be highly energetic (peaking around the evaporation peak at around 1 MeV). When going through water, the initially high-energetic neutrons are subject to elastic collisions with the hydrogen nuclei, transferring them part of the energy and leading to a flatter distribution of neutron energy. In addition, the neutron moderation has also an important role in improving the resolution of the measurements [10].

1.2.5 The neutron beamlines

After being moderated through water, the neutrons begin travelling toward the experimental areas. The neutrons directed toward EAR1 travel inside a 185 m horizontal tube kept under vacuum. A schematic view of the vacuum tube is shown in Fig. 1.6 [16]; it consists of four sections made from stainless steel with a diameter that reduces progressively from 80 cm to 40 cm. Two *collimators* are installed along the line: their purpose is to remove the halo of the neutron beam to deliver it to EAR1 in the optimal shape for the measurements.

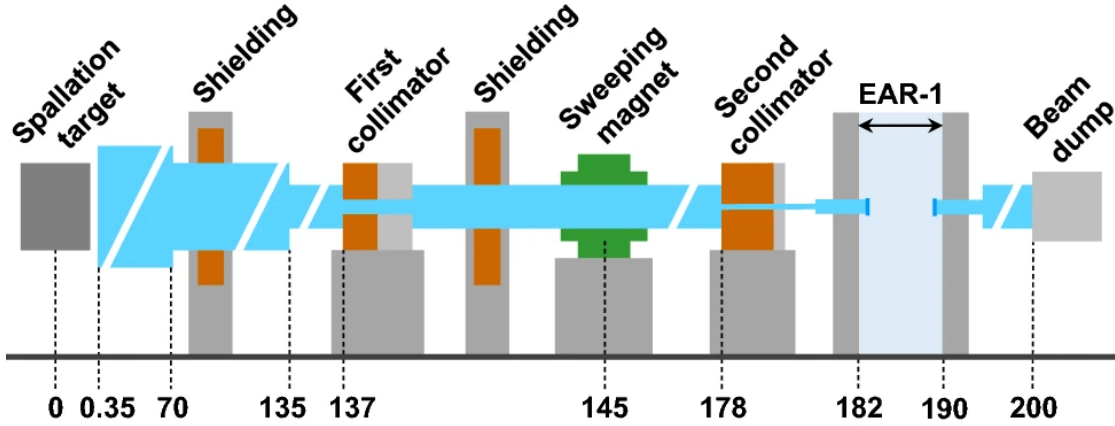


Figure 1.6. Schematic view of the horizontal neutron beamline [16]. It includes a stainless-steel beam pipe under vacuum, two collimators to shape the neutron beam, a permanent magnet to sweep away charged particles from the neutron path, and a beam dump to absorb it. The image also shows the distance (in meters) of the different components from the target.

The spallation reaction does not produce only neutrons, but also many other secondary particles that can pollute the measurements, including γ -rays. The secondary particles that have a charge are swept away from the neutron path by a *sweeping magnet* installed on the line, while other sources of background (see Sec. 1.2.6) are minimised by shielding blocks. The sweeping magnet is a samarium-cobalt permanent magnet composed of 220 blocks of $\text{Sm}_2\text{Co}_{17}$ in an iron yoke and provides a permanent magnetic field of 0.38 T.

The beamline also includes a neutron filter. It is composed of a box with a series of plates of different materials and thicknesses, which can be inserted individually on the neutron path. The different plates can filter specific neutron energies, as well as photons that can be source of background.

The beamline extends to EAR1 where different detectors are installed during the runs of physics experiments to perform time-of-flight measurements. Finally, the beamline continues for 12 more meters and ends with a *beam dump*, an assembly of polyethylene and cadmium foils that absorb the neutron beam. The distance between the detectors and the beam dump is important to prevent backscattered neutrons from lowering the quality of the measurements.

Another neutron beamline is installed vertically above the target and leads to the second experimental area, EAR2 (Fig. 1.7). Like the horizontal beamline, it includes two collimators, a

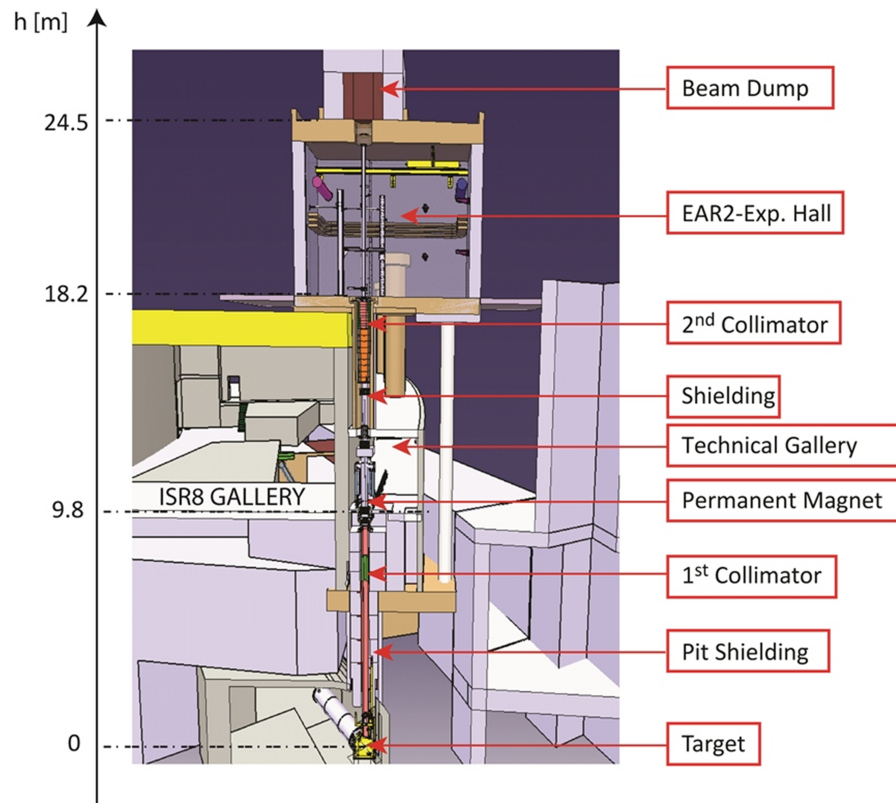


Figure 1.7. Section of the vertical neutron beamline (3D model). The vertical neutron beamline includes a stainless-steel beam pipe under vacuum, two collimators to shape the neutron beam, a permanent magnet to sweep away charged particles from the neutron beam, and a beam dump to absorb it. The image also shows the distance (in meters) of the different components from the target.

cobalt-samarium permanent sweeping magnet (composed of 168 blocks of $\text{Sm}_2\text{Co}_{17}$ providing a magnetic field of 0.25 T), a neutron filter box, and a low background beam dump [17].

The two experimental areas are type A work sectors, where unsealed radioactive sources can be handled. This makes possible to minimize the materials needed for the experimental samples to the ones strictly of interest for the measurements, without additional structural parts that would induce background and decrease the quality of the measurements.

1.2.6 The experimental background

The background is composed of all the spurious events affecting the accuracy of the measurements. It is provoked by secondary particles generated during the spallation process, by decay of other particles, by the interaction of particles with the materials surrounding the neutron beamline, and by γ -rays. Moreover, the samples used to perform the measurements in the experimental areas are themselves a source of background due to neutron and γ -ray scattering.

As already mentioned in Sec. 1.2.5, the background in n_TOF is minimized by the presence of shielding blocks installed along the neutron beamlines, permanent magnets sweeping away the charged particles from the neutron beam, and filters.

Another important source of background in time-of-flight facilities is the overlap between consecutive neutron pulses: if they are generated at high frequency, the slowest neutrons of a pulse can reach the experimental areas later than the fastest neutrons of the next pulse. In n_TOF this does not occur since the maximum pulse frequency is limited by the PS, which can deliver a proton pulse every 1.2 s. This time interval is much longer than the time-of-flight of the slowest neutrons (thermal neutrons have an energy of 0.025 eV and reach EAR1 in about 85 ms), and therefore n_TOF is not affected by any of these *wrap-around* effects.

The high-energy charged particles not removed by the permanent magnets and the γ -rays reaching the experimental areas constitute what is called γ -flash. The γ -flash reaches EAR1 in about 600 ns and EAR2 in 60 ns after the interaction between proton beam and target. It has the useful role of defining the instant zero of the time of flight, but has the drawback of blinding the detectors for a certain time. If it is too strong, the γ -flash can blind the detectors long enough to prevent any analysis of high-energy neutrons, the first ones arriving to the experimental areas.

Additional γ -rays can be emitted as a result of secondary reactions taking place after spallation in the target or in other components of the line: these γ -rays arrive to the experimental areas with a delay, interfering with the measurements.

1.2.7 The neutron flux

The neutron yield at n_TOF is very high, producing up to 300 neutrons per impacting proton [14]. Nevertheless, only a fraction of them reaches the experimental areas. In general, a longer flight path reduces this fraction. In n_TOF, the number of neutrons reaching the experimental areas is in the order of 10^6 n/cm² per pulse in EAR1 and 10^8 n/cm² per pulse in EAR2. Thanks to the high instantaneous yield at the source, these values are high if compared to other similar facilities, especially if the length of the flight path is taken into account. A longer flight path allows n_TOF to have a better energy resolution for a fixed amount of neutrons reaching the detectors [10]. Moreover, this high amount of neutrons is delivered instantaneously (i.e., in a single quick pulse), providing more accurate measurements for radioactive samples: since their radioactivity is also a source of background, a high instantaneous neutron flux provides a better signal-to-background ratio.

1.2.8 The neutron beam energy resolution

Through the time-of-flight method, the neutron speed and kinetic energy can be measured knowing two parameters: the length of the flight path and the time needed to run across it. The resolution ΔE_n with which the neutron energy spectrum can be measured is then related to

the uncertainty ΔL and ΔT in the knowledge of these two parameters. The following relation can be used [10]:

$$\Delta E_n = 2E_n \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta T}{72.29826L}\right)^2} E_n \quad (1.1)$$

Below 1 MeV, the resolution is mainly influenced by the moderation process, which is affected by an intrinsic uncertainty due to its nature of stochastic process. At high energies (> 1 MeV) the main source of uncertainty is given by the duration of the proton bunch striking the target, remarking the importance of a short pulse (7 ns RMS in n_TOF).

For a certain neutron energy, the *resolution function* is defined as the time spread of the neutrons coming out from the target-moderator assembly. It can be expressed in terms of λ , an equivalent distance added to the geometrical flight path length L so that the total apparent flight path is equal to $\lambda + L$ (Fig. 2.6) [10].

1.2.9 Comparison with other neutron sources

Table 1.1 [18] lists the different neutron facilities in the world, dividing them in two groups: facilities where the primary source of neutrons is an electron beam, and facilities where it is a proton beam. In addition, the Neutrons For Science (NFS) facility in Caen (France) uses as primary source a deuteron beam on a beryllium target. The GELINA facility at the Joint Research Centre in Geel (Belgium) is based on a linear electron accelerator impinging on a mercury-cooled uranium target [19, 20]. The Gaerttner LINAC Center at the Rensselaer Polytechnic Institute in the United States uses an electron beam with a water-cooled tantalum target [21, 22]. Tungsten targets with tantalum cladding are employed in the Lujan Center at the Los Alamos Neutron Source Center (LANSCE) in the United States [23]. Neutron production targets based on lead are employed at the Paul Scherrer Institute (PSI) in Switzerland [24] and in the neutron time-of-flight setup nELBE at the Helmholtz-Zentrum Dresden-Rossendorf in Germany [25]. In the case of the SING source, the lead is solid without beam but operates in liquid state inside a Zircaloy cladding during operation [26], while in case of nELBE lead is in liquid state at all times. Solid lead targets for neutron production are utilized for the Lead Slowing Down Spectrometer (LSDS) at the LANSCE facility [27].

A comparison of the neutron energy distributions at major TOF facilities, currently in operation or close to completion, is shown in Fig. 1.8 [18].

Table 1.1 and Fig. 1.8 show the main strengths of the n_TOF source compared to other facilities, despite the lower average beam power on target:

- A proton beam as primary source, which generates lower γ -flash than electron sources.
- With the high energy of the impacting proton beam (20 GeV), the base material of choice (pure lead) is characterized by high neutron yield (about 300 neutrons per impacting proton [14]), high transparency for neutrons at energies lower than 1 MeV, and relatively

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Table 1.1. Comparison of several neutron facilities in the world (the list is not exhaustive) [18].

Facility	Location	Beam	Energy (MeV)	Target	Pulse width (ns)	Beam power (kW)	rep. rate (Hz)	Flight paths (m)	Neutrons per pulse
RPI	Troy, USA	e	60	Ta	5	0.45	500	15–250	3.6×10^9
ORELA	Oak Ridge, USA	e	60	Ta	5000	>10	300	15, 25	4.8×10^{11}
GELINA	Geel, Belgium	e	180	Ta	2–30	60	12–1000	9–200	1×10^{12}
nELBE	Rossendorf, Germany	e	100	U	1	10	40–800	5–400	4.3×10^{10}
IREN	Dubna, Russia	e	40	L-Pb	0.01	40	500 000	4	5.4×10^7
PNF	Pohang, Korea	e	30	W	100	0.42	50	10–750	7.7×10^{10}
KURRI	Kumatori Japan	e	75	Ta	2000	0.09	12	11	1.7×10^{10}
		e	46	Ta	2	0.046	300	10, 13, 24	2×10^9
		e	30	Ta	4000	6	100	10, 13, 24	8×10^{10}
LANSCE-MLNSC	Los Alamos, USA	p	800	W	135	800	20	7–60	7×10^{14}
LANSCE-WNR	Los Alamos, USA	p	800	W	0.2	1.44	13 900	8–90	8×10^9
n_TOF	Geneva, Switzerland	p	20 000	Pb	6	10	0.4	20, 185	2×10^{15}
MLF-NNRI	Tokai, Japan	p	3 000	Hg	1000	1000	25	30	1.2×10^{17}
ESS	Lund, Sweden	p	2 000	W	2860	5000	14		
SNS	Oak Ride, USA	p	1 000	Hg	700	1400	60		
ISIS-TS1	Oxfordshire, UK	p	800	W	100	240	50		
CSNS	Dongguan, China	p	1 600	W		100	25		
NFS	GANIL, Caen, France	d	40	Be	<0.5	2	150k–880k	5–30	

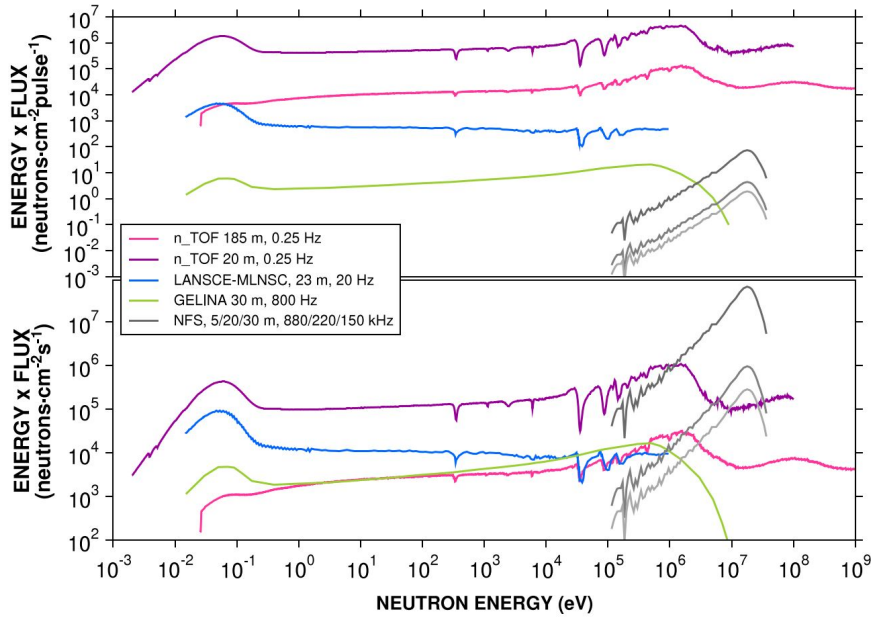


Figure 1.8. Energy distribution of neutrons for several time-of-flight facilities [18]. Top: instantaneous flux (neutrons in a single pulse). Bottom: average flux (neutrons per second). Expressed as neutrons per logarithmic energy bin (per unit of lethargy), either per second (average flux) or per pulse (instantaneous flux).

low activation.

- The low repetition rate avoids overlap between different neutron bunches.
- The high number of neutrons delivered in a very short bunch (7 ns RMS) offers a very low signal-to-background ratio. This is particularly useful with radioactive samples, characterized by higher background due to their radioactivity.

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- The high neutron yield at the source offers the possibility of having longer flight paths and higher resolution while keeping a reasonable neutron flux at the experimental areas, or higher neutron flux with shorter flight paths.

These features make the n_TOF neutron source an ideal instrument for high-precision cross-section measurements of radioactive isotopes available in small quantities or with very high specific activity.

1.3 The previous n_TOF targets and rationale for a new target

1.3.1 Thermal effects due to beam-target interaction

When a proton beam hits the target, parts of the beam energy dissipates in form of heat in the target. A 20-GeV beam with 10^{13} protons holds a kinetic energy of 32 kJ. About half of this energy is dissipated as heat in the target, resulting in a temperature spike.

The energy is not dissipated uniformly but as a function of the beam shape impacting the target. For the purpose of the thermal analyses summarized in the following sections, the beam profile along both the vertical and horizontal axis of the beam cross-section is assumed Gaussian. In this work, one standard deviation of these Gaussian profiles will be referred to as 1σ , while four standard deviations as 4σ . The distribution along the beam axis of a proton pulse is also assumed to be Gaussian.

In theory, the beam could be delivered to the target every 1.2 s for a maximum rate of 0.83 Hz, but the actual rate is generally lower: the Proton Synchrotron operates in series of 1.2-s cycles called *supercycles* that, once configured, are repeated indefinitely. Each 1.2 s cycle in a supercycle can potentially deliver one proton beam pulse to the n_TOF target, but the cycles in each supercycle are shared among different experimental facilities, one of which is n_TOF. Moreover, a further limitation to the amount of pulses in a supercycle delivered to n_TOF can be imposed by the thermomechanical constraints of the target in case the absorbed average power brings the target to unacceptable temperature values (see Chap. 2).

1.3.2 The n_TOF Target #1

The n_TOF facility was commissioned in 2000 with the 185-m horizontal flight path, and operated until 2004. The first-generation target (Target #1, Fig. 1.9) was constituted by a series of pure-lead bricks [28], stacked together to form a massive block measuring $80 \times 80 \times 40 \text{ cm}^3$.

The target was designed for the beam parameters listed in Table 1.2. It was cooled by demineralized water with a flow rate of $22 \text{ m}^3/\text{h}$. The water layer downstream of the target was 5-cm thick and also acted as neutron moderator.

With the target operating at stable nominal conditions, a peak temperature of 165°C was



Figure 1.9. Photo of the n_TOF Target #1: it is composed of a water-cooled pile of lead bricks stacked together to form a massive block measuring $80 \times 80 \times 40 \text{ cm}^3$).

Table 1.2. Beam parameters assumed for the design of the n_TOF Target #1 [29, 30].

Pulse intensity:	$7 \times 10^{12} \text{ p}^+$
Beam momentum:	$20 \text{ GeV}/c$
Pulse energy:	22.4 kJ
Pulse length:	$25 \text{ ns } (4\sigma)$
Beam size:	$7.8 \text{ mm} \times 5.6 \text{ mm } (1\sigma)$
Number of pulses per supercycle:	4
Supercycle length:	14.4 s
Average intensity:	$1.94 \times 10^{12} \text{ p}^+/\text{s}$
Average current:	$0.31 \text{ }\mu\text{A}$
Average power:	6.23 kW (about half absorbed by the target)
Peak current:	71.6 A
Peak power:	1.43 TW
Peak energy deposition:	$29.7 \text{ J}/\text{cm}^3$
Single pulse temperature spike:	20.3°C

estimated by means of finite-element thermal simulations (Fig. 1.10 [30]). Six thermocouples were placed on the target to monitor its temperature and confirm the expected thermal response (Fig. 1.11 [29, 31]). Each temperature spike in Figure 1.10 and 1.11 corresponds to a beam pulse hitting the target. It is followed by thermal diffusion and cooling down for 3.6 s, until the next pulse reaches the target. During stable and continuous operation, the average temperature rises pulse after pulse until a steady-state condition is reached, where every temperature transient following a pulse is identical to the previous one.

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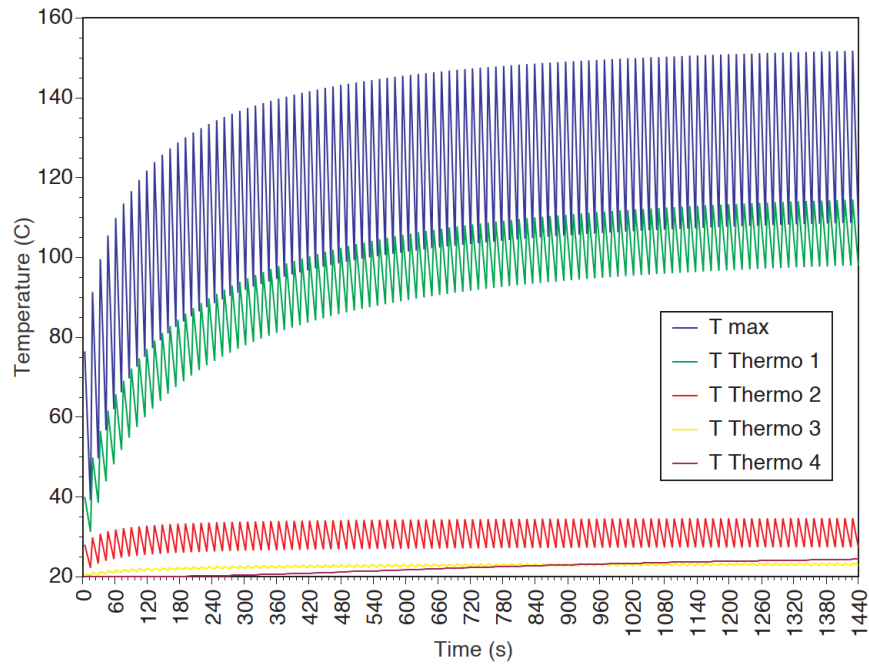


Figure 1.10. Estimation, by finite-element simulations, of the temperature evolution in Target #1 in nominal conditions (four pulses of 7×10^{12} p⁺ every 14.4 s). The evolution of the highest temperature is plotted, as well as the estimated temperature values where the thermocouples were located.

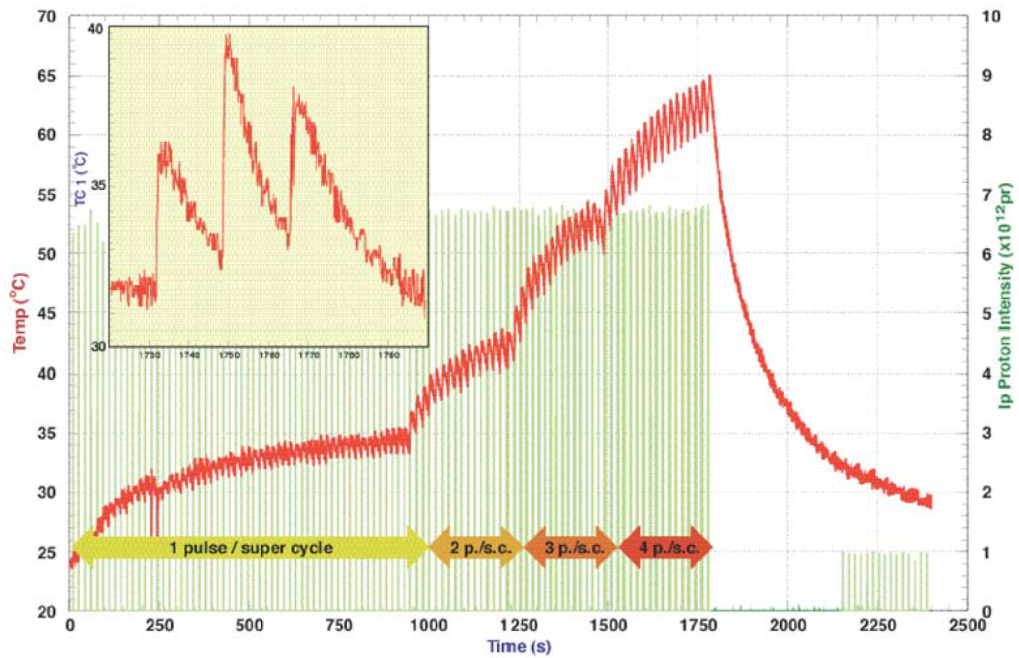


Figure 1.11. Thermocouple measurements in Target #1.

Chapter 1. The n_TOF neutron facility at CERN

In 2004, after three years of successful operation, an abnormal increase of radioactivity in the cooling circuit was observed and the facility was stopped for three years (Fig. 1.12 [32, 33]). The issue was ascribed to inefficient cooling at the beam impinging point and lack of chemical control of the cooling water, facilitating pitting corrosion and contamination of water with radioactive lead spallation products [34]. The target was extracted and its surface scanned via laser scan, showing the presence of a hole in the lead block at the beam impact spot (Fig. 1.13). These observations confirmed that the target was damaged during operation and that eroded lead particles and spallation products entered the cooling circuit.

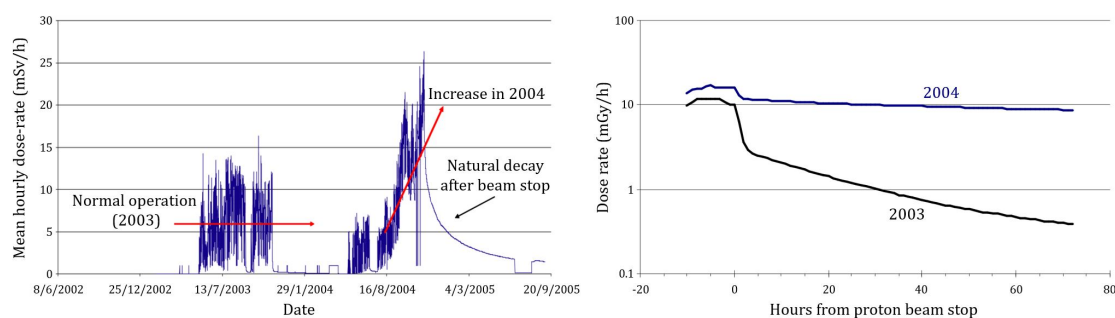


Figure 1.12. Ionizing radiation dose rate (measured by a ionization chamber) close to the filters of the cooling circuit. Left: sudden increase of activity in 2004. Right: comparison of the decay curve (after stopping the beam) before and after the event, indicating the dissolution in water of isotopes with much longer half-lives. This change is compatible with the onset of pitting corrosion, confirmed by the observations on the target after removal.

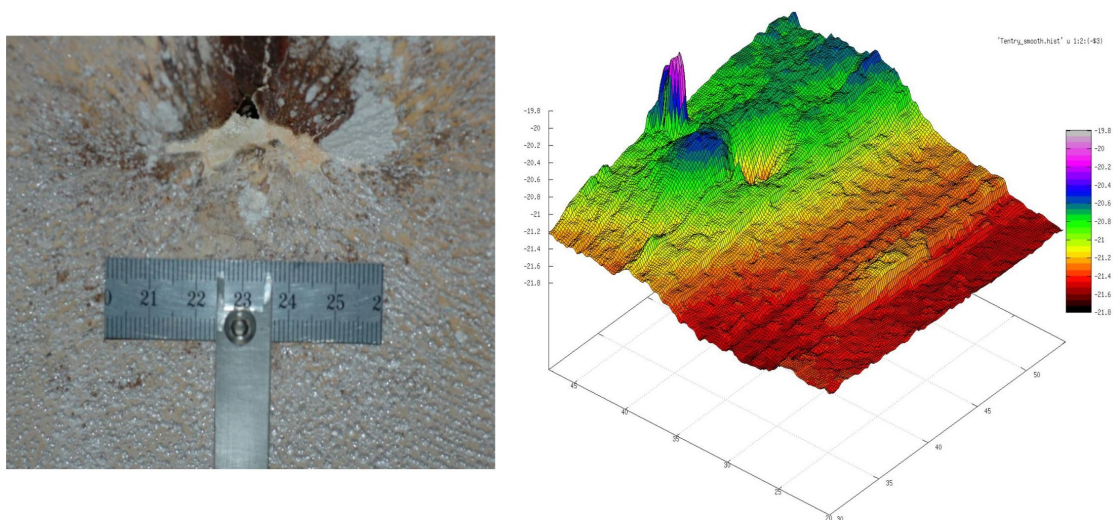


Figure 1.13. Damage at the beam impact spot on the n_TOF Target #1 [35]. The plot on the right shows the results of laser scanning measurements (in centimeters) around the hole on the lead surface.

1.3.3 The n_TOF Target #2 and rationale for a new target

The design of the second-generation target (Target #2) was aimed at addressing the operational concerns of Target #1 [36]. Target #2 is a cylinder with diameter of 60 cm and axial length of 40 cm, cooled by water with a flow rate of 7 m³/h (Fig. 1.14). A separate moderator assembly, made of aluminum alloy, was added to have the possibility of using a moderator fluid different than the coolant. The moderator fluid used was borated water (boron concentration of 1.28 wt%), which reduced the background for the measurements in EAR1 [37]. The target core is enclosed in an aluminum vessel and it is slightly smaller than Target #1, so the entire assembly was fitting inside the old target container, which acted as secondary containment vessel.

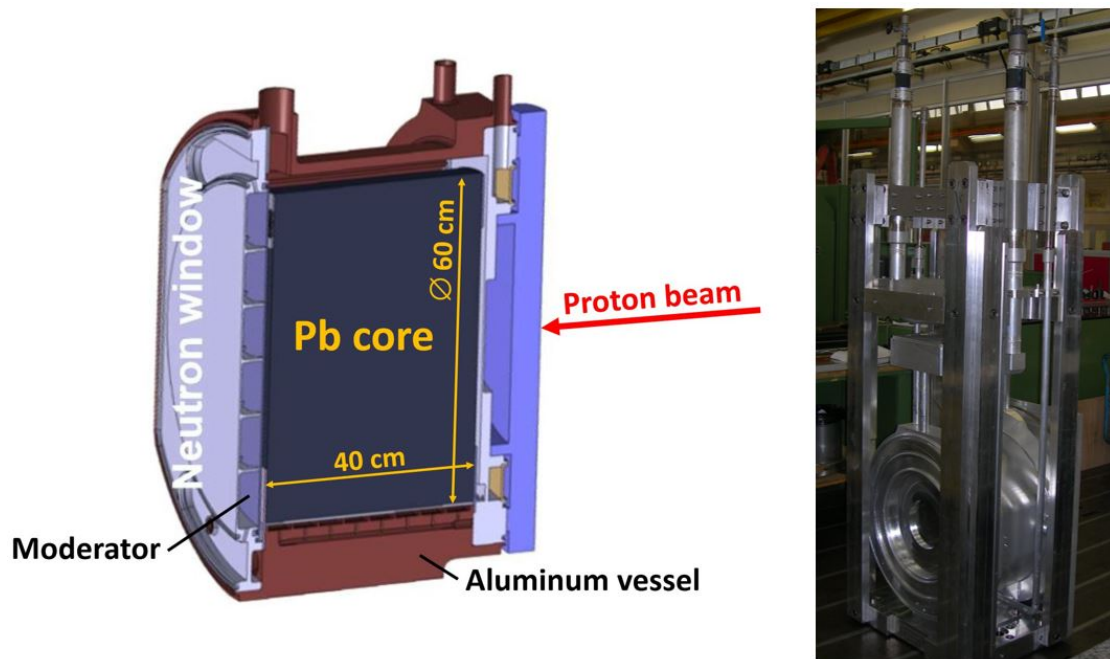


Figure 1.14. Left: 3D model (cross-sectional view) of Target #2. The target core is a cylinder with a diameter of 60 cm and a length of 40 cm, cooled by water. The target has a separate water moderator with an aluminum casing. Right: photo of the target in its cooling vessel and supporting frame.

The target was installed at the end of 2008 and started operating in 2009. Some critical aspects of the design were highlighted, like the thin aluminium window separating cooling and moderator circuits. The window could not be thicker to avoid increasing photon background in the experimental areas, and was considered at long-term risk of corrosion and failure [33].

Another critical aspect was the direct contact between pure lead and cooling water, as with Target #1, with the risk of erosion-corrosion phenomena and contamination of the cooling water with radioactive spallation products from lead. Different measures were taken to reduce this risk. The circulation of cooling water was improved, the maximum average beam intensity was limited to 1.67×10^{12} p⁺/s, and the proton beam impacting the target was defocused to

spread the dissipated heat over a larger volume. Moreover, the water chemistry was controlled and kept within very tight operational constraints to minimize its corrosion capacity [33].

Taking these critical aspects into account, a target lifetime of ten years was estimated, after which the target would have to be replaced. A sudden rise in the radioactivity of the cooling water was detected in the last years of target operation and an endoscopic inspection also revealed first signs of corrosion of the *neutron window*, the window separating the target moderator from the environment (Fig. 1.15) [38].



Figure 1.15. First signs of corrosion on the neutron window, observed by endoscopic inspection in 2014 [38].

The contamination of the water circuit was controlled by gamma spectrometry and liquid scintillation (for tritium) measurements on samples of water routinely taken from the circuits. The results of the measurements on samples taken between December 2014 and January 2016 are summarized in Table 1.3. In 2015, a significant increase of radioactivity was observed in August and confirmed in October. The water circuit was purified by an ion exchanger. The ion exchanger cartridge was isolated from the circuit, which was then connected to a spare cartridge. This explains the reduction in activity on the 12th of October 2015 in Table 1.3, due to the dilution with the non-activated water inside the spare cartridge. After the change, the specific activity measured in the circuit decreased but remained rather high if compared with the reference values from previous runs.

In 2014 the new experimental area (EAR2) was built 20 m above the target [39]. Even if the design of Target #2 included the possibility of inserting a vacuum tube on top of the spallation target, the resolution in EAR2 was not optimal, since the target shape was not conceived for this experimental area: the moderation of the neutrons directed upwards was achieved with an irregular thickness of cooling-water volume above the lead target core.

In case of issues with the neutron window or with contamination of the water circuit, the

Table 1.3. Specific activity measured in the samples of water coming from the cooling circuit between December 2014 and January 2016. The activity of tritium (^3H) was measured by liquid scintillation while all other radionuclides were measured by gamma spectrometry. From October 2nd 2015 to October 12th 2015, the ion exchanger cartridge in the circuit was switched with a spare one. In January 2016, two samples were analyzed: the first sample was taken before the ion exchanger cartridge and the second one after [33].

Specific activity in Bq/g		TOF56502/3		TOF55511	TOF55510	TOF55509	TOF55508	TOF55507	TOF55503	TOF45500
		27-Jan-16		17-Nov-15	23-Oct-15	12-Oct-15	02-Oct-15	12-Aug-15	04-Avr-15	19-Dec-14
		Before	After							
Au-195	183 days	0.29	0.30	5.25	3.14	9.47	33.20	9.05	0.33	0.14
Hg-203	46.6 days	0.05	0.04	3.22	0.61	3.79	3.34	-	0.07	0.07
Os-185	93.6 days	0.13	0.10	2.40	1.25	4.05	12.00	3.45	0.20	0.05
Lu<Hf172	1.87 years	0.10	0.06	0.71	0.43	1.23	6.35	1.29	0.16	0.03
Lu-173	1.37 years	0.06	0.02	1.29	0.87	2.15	7.77	2.36	0.03	0.08
Hf-175	70 days	0.08	0.04	3.77	1.93	5.68	18.80	6.28	0.11	0.08
H-3	12.32 years	18000	18000	15000	13000	13000	19000	15000	7000	7000

operation of the n_TOF facility may have to be stopped until replacement. A repair is not possible because of the target design and the high estimated radioactivity levels around it, approaching 100 mSv/h [33].

1.4 Thesis outline

The critical aspects of Target #2, such as the thin neutron window, the contamination of water in the cooling circuit with lead spallation products, and the impossibility to repair the target, justified the replacement of the target with a new concept that removes or minimizes the mentioned risks.

The design studies for the new target started in 2015. Chapter 2 describes the design process that started from a series of potential target concepts and converged towards the final design adopted for the new target. The objectives of the new design are outlined in terms of physical and thermo-mechanical performance, and a background on the methodologies used in the different design phases is provided. Different design solutions are compared based on physics studies and thermo-mechanical simulations, leading to the selection of a specific solution. The content of this chapter has been published in Ref. [40].

Chapter 3 details the final design adopted for the new target, consisting of a series of lead slices supported by an aluminum anti-creep structure and cooled by nitrogen. Novel approaches to simulate material response are presented and degraded operational scenarios are analyzed. The content of this chapter has been published in Ref. [41].

Chapter 4 describes the design and construction of a small-scale prototype of the new target and a prototype for an alternative concept consisting of a water-cooled Ti-6Al-4V-clad lead design. The two prototypes were subjected to a test under beam irradiation in a dedicated CERN facility. The chapter also shows the results of post-irradiation examinations performed

to assess the conditions of the two prototypes.

Chapter 5 describes the execution of mechanical characterization tests on pure lead and the proposal of a new constitutive model to better reproduce the evolution of pure lead stress-strain behaviour when subjected to repeated impacts of proton beam pulses. The proposed model is able to reproduce complex effects in the material behaviour (such as cyclic hardening, Bauschinger effect, and non-Masing effect) that are not represented in commonly used simpler models.

The thesis ends with some conclusions drawn from the design and experimentation efforts described and with recommendations for future studies that would further improve the computational models used to simulate materials subjected to repeated beam-pulse impacts.

2 The design studies for the new n_TOF target

2.1 Introduction

The design studies for the new target started in 2015. The installation of the new target in the n_TOF facility was planned for the CERN Long Shutdown 2, which started in 2019 and ended in 2021.

During the four years of design studies, different target concepts were examined in five project reviews by panels of experts in different physics and engineering fields, from CERN and other neutron sources in the world. The master plan of the work described in this thesis is shown in Fig. 2.1.

	Run 2						Long Shutdown 2					
Year	2016		2017		2018		2019		2020		2021	
Semester	1	2	1	2	1	2	1	2	1	2	1	2
Preliminary design studies			①									
Prototyping work												
Detailed design					②	③						
Beam irradiation tests												
Construction							④					
Cold test												
Installation										⑤		
Commissioning with beam												

1. Preliminary Design Review (June 2017)
2. Intermediate Engineering Design Review (May 2018)
3. Internal Design Review (November 2018)
4. Production Readiness Review (May 2019)
5. Target Installation Review (February 2021)

Figure 2.1. Master plan of the design and production of the n_TOF Target #3. The project has been reviewed by panels of experts from CERN and other neutron source facilities in five project reviews, held at major project milestones.

The main scientific and technological objectives to be pursued during the conception of the new design were:

- Limiting erosion-corrosion phenomena and contamination of the cooling medium with lead spallation products.
- Improving neutron fluence and resolution for EAR2, thanks to the addition of a dedicated moderator.
- Increasing the maximum beam pulse intensity that can be delivered on the target (up to 10^{13} protons per pulse).
- Preserving the EAR1 physics performance in terms of neutron fluence, background, and resolution.
- Preserving or improving background conditions in the experimental areas.

In a preliminary design stage, described in Sec. 2.2, six different concepts were evaluated. Based on these preliminary studies, three of them were discarded while three target concepts were retained and two more added for an advanced stage of design studies, described in Sec. 2.3. After this advanced stage of design studies, there was a final design stage where only two concepts (including the adopted design choice described in detail in Chap. 3) have been examined. For these two final concepts, target prototypes were built and subjected to a test under proton beam irradiation, described in Chap. 4 [40].

The design studies relied heavily on numerical methods to simulate the physics and thermo-mechanical performance of the different target solutions considered. The following subsections introduce the concepts and the tools useful to understand the analyses performed: Monte Carlo particle transport simulations, Finite Element Method (FEM) and Computational Fluid Dynamics (CFD).

2.1.1 Particle transport simulations with FLUKA Monte Carlo code

Monte Carlo methods are a broad class of computational algorithms relying on random sampling and statistical trials. They are successfully employed to solve many complex physical problems involving a large number of coupled degrees of freedom, which are difficult or impossible to solve with other methods. These methods are widely used to solve particle transport problems and random walk simulations based on measured interaction probabilities between particles and matter [42].

The FLUKA code (*FLUktuierende KAskade* or *Fluctuating Cascade* [43–46]) is a general purpose tool based on the Monte Carlo method for calculations of particle transport and interactions with matter. It is jointly developed by CERN and the Italian National Institute of Nuclear Physics (INFN). It can simulate a large set of particles, like photons, electrons, neutrinos,

muons, hadrons, antiparticles, and heavy ions, all over a wide energy spectrum. These simulations are useful for a wide range of applications: design and activation of radiation shieldings, energy deposition in materials, radiation damage in materials and electronic components, target design, calorimetry, radioactive dose-rate calculations, detector design, nuclear technology, cosmic ray physics, neutrino physics, radiotherapy and hadron therapy, management of radioactive waste and estimation of its environmental impact.

The main applications in the context of the n_TOF target design are: the estimation of energy deposition in target components interacting with the impinging proton beam; the study of motion and interactions of neutrons, photons, and other particles to estimate the performance of different target designs in terms of the quantities described in Sec. 1.2 (neutron flux, resolution function, and background).

The FLUKA Monte Carlo simulations for the different target designs examined in this work were performed by the SY-STI-BMI section at CERN.

2.1.2 Thermal and structural simulations with FEM

The thermo-mechanical analyses performed in this work aim to estimate temperatures, deformations and stresses in solids using the theories of continuum mechanics [47]. The knowledge of the time evolution of these parameters in a physics problem requires the definition of boundary conditions.

For complex problems, these calculations can be performed by numerical integration exploiting the Finite Element Method (FEM) [48]. This method is integrated in commercial software packages for structural design like ANSYS and LS-DYNA [49], used for this work. The method consists first in dividing the system into a series of subdomains (the finite elements) on which the equations of a certain physics problem are applied (like the heat transfer equations and the Fourier's law for thermal problems, and the Newton's laws of motion for mechanical problems). These equations locally approximate the original complex equations to be studied and are then solved by standard numerical integration methods. The constitutive models defining the relation between stress and strain in a material are formulated on the basis of the *theory of elasticity* [50] and the *theory of plasticity* [51, 52].

In the thermal analyses presented in this work, the boundary conditions to be defined are heat sources, mainly represented by the deposition of energy density deriving from the interaction with the proton beam, and heat sinks, mainly represented by the heat transferred to coolants. The heat transferred to coolants is generally defined by the *heat transfer coefficient* $h = q/\Delta T$, where q is the heat flux between solid and coolant per unit area and ΔT is the temperature difference between them. If all the physics parameters and boundary conditions are time-independent, the problem is referred to as a *steady-state thermal* problem, otherwise it is referred to as a *thermal transient* problem.

In the structural analyses, the boundary conditions are represented by external forces and

pressure fields on surfaces, weight of materials, temperature distributions resulting from the thermal analyses, and constraints to displacements and deformations of solids represented by supports or contacts. A simulation is *quasi-static* if the inertial and viscous components in the equations of mechanical equilibrium are negligible compared to the elastic terms. When these components are relevant, *dynamic simulations* are needed. In some of the simulations presented in this work, the inertial effects represent the dominant component due to the impulsive heat load induced by interaction with the proton beam. The material in the vicinity of the beam axis undergoes a sudden temperature spike and a rapid thermal expansion, which violently pushes the surrounding material radially and starts the propagation of a *radial stress-wave*. The existence of this effect can be directly derived from the Newton's laws of motion in a continuum solid [53]. In a similar way, the sudden thermal expansion and protrusion of the surfaces incident to the beam axis generate *longitudinal waves* starting from the surfaces and propagating perpendicular to them (Fig.2.2).

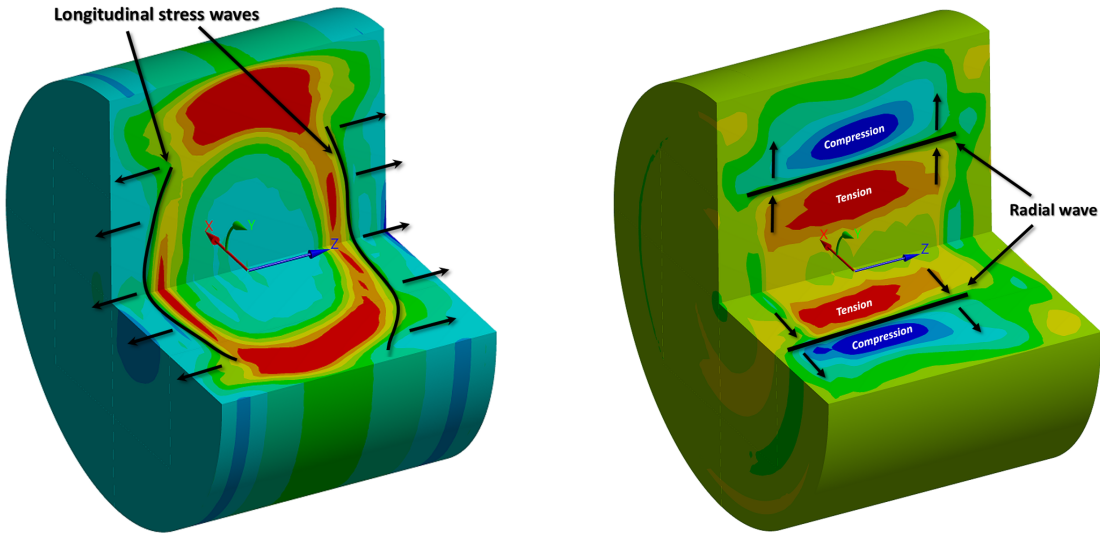


Figure 2.2. Longitudinal and radial stress waves in lead (section view) provoked by the impulsive thermal expansion of material around the axis, due to the impact with the proton beam. The colors are qualitatively showing the sign of the maximum principal stress: the red areas are stressed in tension, while blue areas are in compression.

2.1.3 Fluid simulations with CFD methods

Computational Fluid Dynamics (CFD) uses numerical analysis to solve problems of continuum mechanics involving fluid flows. These analyses are used in the present work to compute temperature, pressure, and velocity of the fluids used as target coolants. The definition of the boundary conditions consists, in this case, in assigning the value of the physics parameters at the inlets and outlets of the simulated circuits.

The equations to be solved by numerical integration are, in this case, the Navier-Stokes equations [54]. In the case of *Conjugate Heat Transfer* analyses, the laws of thermal conduction

for solids are also included and it is possible to perform a coupled thermal analysis with fluid-solid interaction in the same simulation. As with FEM, a domain discretization is also needed: different methods are available, the most common of which is the *finite volume method* [55].

The results obtained from CFD simulations provide useful information for the design of target cooling systems (like the pressure drop between the inlet and the outlet of the target), as well as parameters needed for the FEM thermal simulations, like the heat transfer coefficient (HTC) at the interface between solids and coolant.

2.2 Preliminary design studies

Figure 2.3 and 2.4 compare the neutron fluence in the EAR1 and EAR2 experimental areas for the six preliminary target design solutions with respect to Target #2, estimated by means of the FLUKA Monte Carlo code. The six preliminary design concepts are described more in detail in the next subsections.

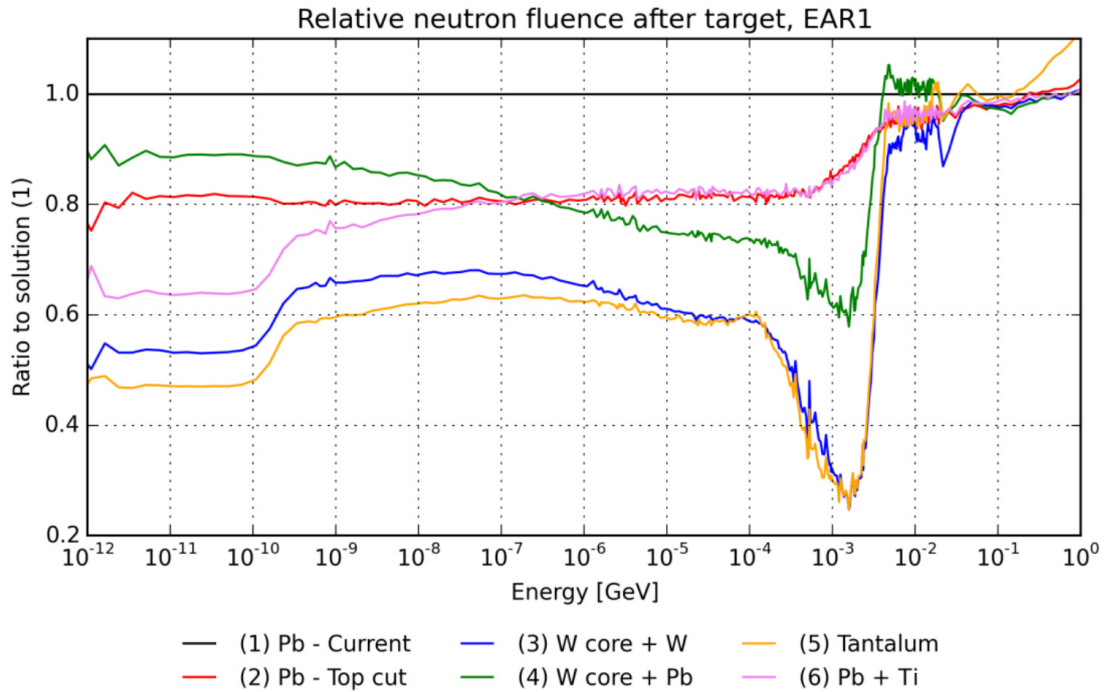


Figure 2.3. The plot shows the neutron fluence in EAR1 for the six preliminary design solutions. The neutron fluence has been estimated by means of FLUKA Monte Carlo code [33].

2.2.1 Second generation n_TOF Target (Target #2) design

The second-generation target core is a pure lead cylinder, 60 cm in diameter and 40 cm in length. It is cooled by water, so it can be subjected to erosion-corrosion phenomena leading to contamination of the water-cooling circuit (Fig. 1.14). Since the vertical experimental area

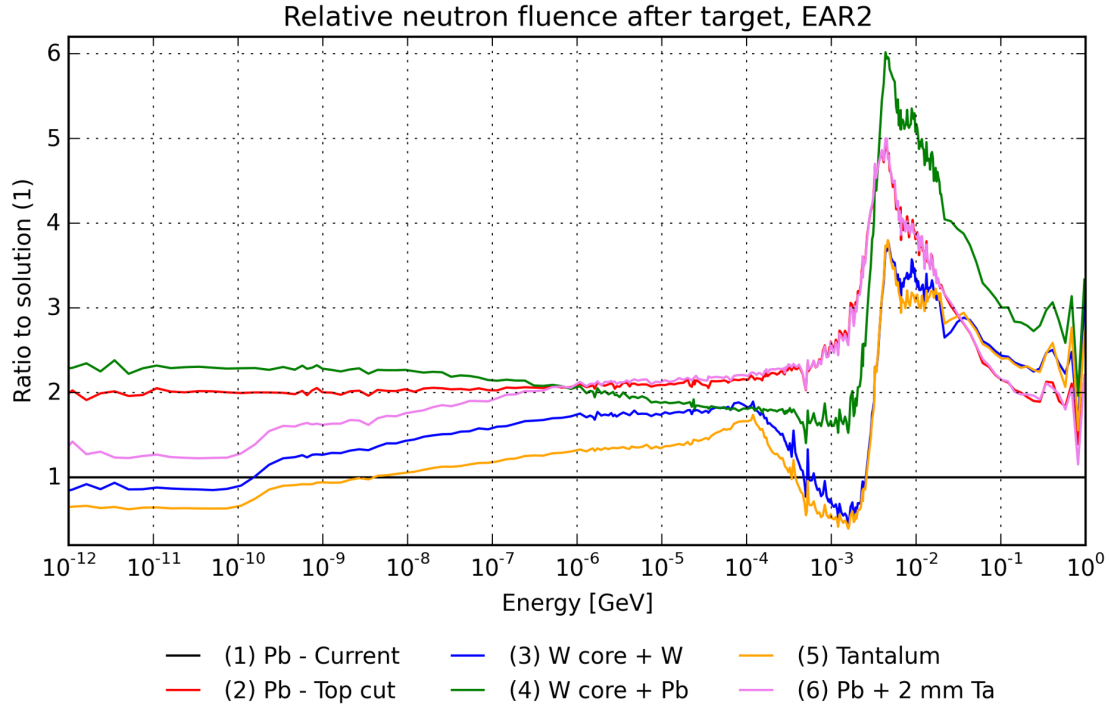


Figure 2.4. The plot shows the neutron fluence towards EAR2 right above the target, for the six preliminary design solutions. The neutron fluence has been estimated by means of FLUKA Monte Carlo code [33].

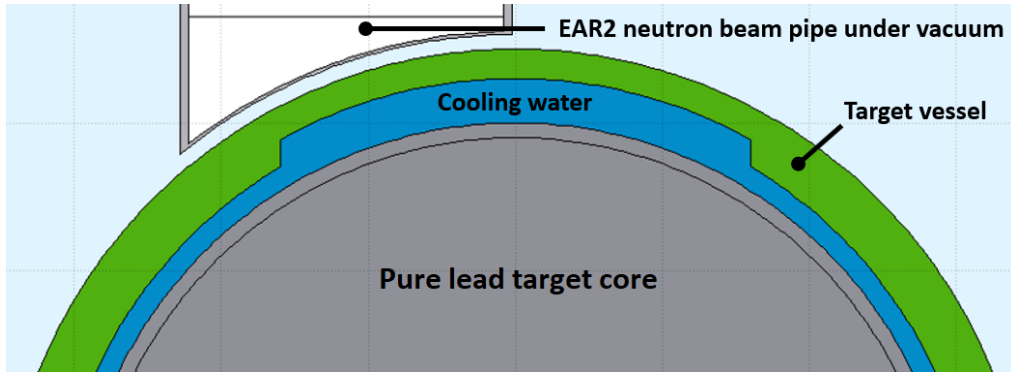


Figure 2.5. FLUKA model used to study the Target #2 concept. The cylindrical shape of the cooling water layer above the lead core, which acts as neutron moderator, leads to poor resolution of the measurements in EAR2.

was not present when the target was designed and constructed, its shape is not optimized for EAR2, since the neutrons directed to this experimental area are moderated by an uneven cooling water layer above the lead cylinder, which has a cylindrical shape functional to the cooling itself (Fig. 2.5). Since the moderating water layer is not constant, each neutron exits the moderator at a different moderating distance. This has a negative impact on the resolution function, which is characterized by a double peak (Fig. 2.6). This design concept is included as it represents the reference to which the other concepts must be compared to.

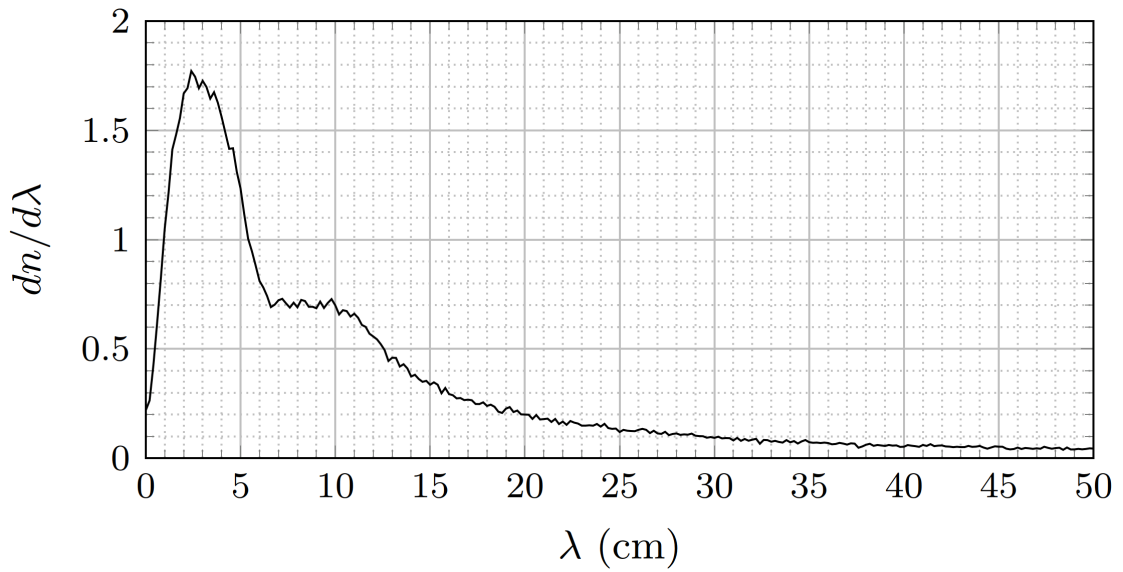


Figure 2.6. Resolution function of Target #2 in EAR2. The 'double peak' structure is caused by the uneven shape of the water volume moderating the neutrons.

2.2.2 Lead cylinder with flat top

This solution was initially proposed with the sole objective of improving the resolution in EAR2 with minimal change compared to the Target #2 concept.

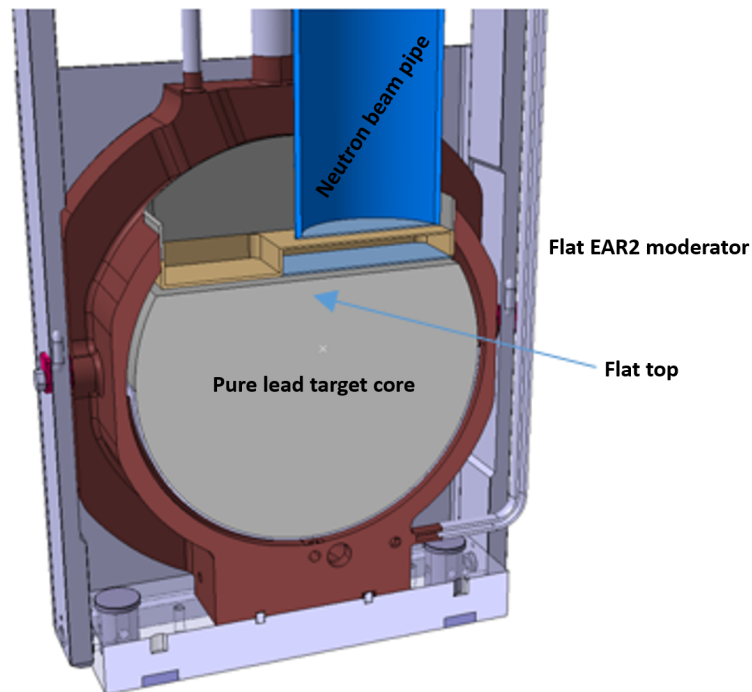


Figure 2.7. Target concept consisting of a pure lead cylinder with a flat top and flat EAR2 moderator. The flat top and moderator improve the resolution function in EAR2.

In this version, the target is no longer a cylinder, but it has a flat top to avoid the irregular shape of the EAR2 moderator and the double peak structure of the resolution function (Fig. 2.7). The distance between the cylinder axis and the horizontal cut at the top was fixed to 15 cm after physics and Monte Carlo optimization studies aimed to find the best compromise between neutron fluence in EAR1 and EAR2. The erosion-corrosion and contamination issues are not addressed by this solution, which was considered a backup choice.

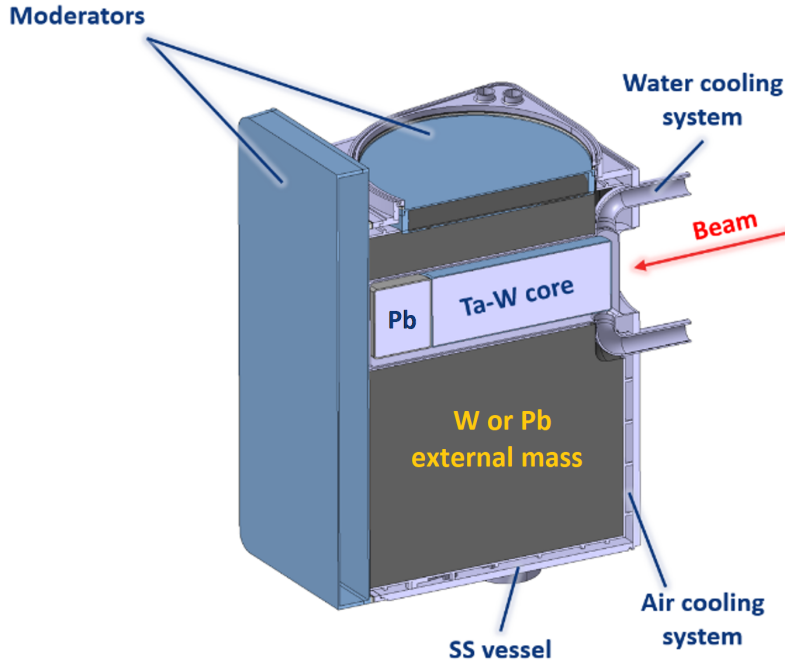


Figure 2.8. Target concept consisting of a tantalum-clad tungsten core surrounded by an external mass of tungsten or lead. The tantalum-clad tungsten core absorbs most of the beam power and has a dedicated water cooling system, while a gas-based cooling system is enough to cool down the external mass.

2.2.3 Tantalum-clad tungsten core surrounded by a tungsten mass

This design concept is composed of a cylinder of tungsten ($\varnothing 10 \times 25$ cm) with a tantalum cladding obtained by hot isostatic pressing (HIP) process, enclosed in a massive tungsten block (Fig. 2.8). The tantalum-tungsten core would be the part directly impacted by beam, and the only one to be actively water cooled. The excellent corrosion resistance of tantalum would solve the issues related to the contamination of the water circuit, while the better thermo-mechanical properties of tungsten and tantalum (compared to lead) would add flexibility on the target operation and not present any thermo-structural limitation in terms of average power dissipated on the target. The HIP process would provide an excellent thermal conductance at the tantalum-tungsten interface. Tantalum-clad tungsten assemblies obtained by hot isostatic pressing have already been researched and successfully tested with beam at CERN [56, 57]. For the external tungsten mass, a forced gas flow or even natural convection

would suffice for an adequate cooling. On the other hand, the EAR1 neutron fluence of this solution is only 25-30% the one of Target #2 around 1 MeV (evaporation peak), and about 60-70% from 1 keV to 100 keV (Fig. 2.3). Since one of the design requirements for Target #3 is the preservation of the physics performance in EAR1 within a reasonable limit, this reduction in neutron fluence was an obstacle to the adoption of this solution.

2.2.4 Tantalum-clad tungsten surrounded by a lead mass

This design solution is similar to the one described in Sec. 2.2.3 and in Fig. 2.8, with the only difference being the external mass made of lead instead of tungsten. This variation provides better physics performance in terms of neutron production and background with respect to the other tungsten-based solution, because of the lower inelastic cross-section of pure lead compared to tungsten. The neutron fluence (Fig. 2.3) is equal to 60-65% the one of Target #2 around 1 MeV. This reduction is caused by the strong inelastic channels in tungsten in the 0.1–1 MeV range. The design is further improved with additional lead downstream of the Ta-W core, which reduces background and increases neutron fluence. Despite the improvements, the neutron fluence is still 25% lower than Target #2 at 1 MeV, so the solution was discarded because of worse physics performances than other concepts.

2.2.5 Tantalum target

This concept consisted in a $50 \times 50 \times 22.5 \text{ cm}^3$ volume of tantalum with water cooling, divided into three slices to increase the surface exposed to the coolant. This solution is technically very simple, although very expensive because of the high cost of the base material. Moreover, the neutron fluence of this solution (Fig. 2.3) is only 20–30% the one of Target #2 around 1 MeV, and about 60–65% from 1 keV to 100 keV. Therefore, this solution was also discarded.

2.2.6 Ti-6Al-4V-clad lead

This design is similar to the pure lead solution with flat top of Sec. 2.2.2, with the addition of a titanium Grade 5 (Ti-6Al-4V) layer protecting the lead core from water corrosion (Fig. 2.9). The choice of the cladding material was the result of an optimization procedure aimed to find the best combination of neutron flux, background, elasticity, corrosion resistance, yield and fatigue strength. The materials considered included: tantalum, niobium, Zircaloy, stainless steel, Inconel, and Nitronic.

This solution is characterized by almost the same neutron fluence in EAR1 and higher neutron fluence in EAR2 than Target #2 (Fig. 2.3), but also by higher photon background due to the titanium Grade 5 layer downstream of the lead core. To avoid excessive background, the Ti-6Al-4V layer must be limited to a thickness of 1 mm. Since the Ti-6Al-4V layer is 600-mm wide, the manufacturing and assembly procedure of this solution turned out to be particularly challenging. Moreover, during operation, the lead core would swell because of

thermal expansion and push the Ti-6Al-4V layer from inside. Such a wide and thin layer of Ti-6Al-4V would have elastic deformations in the order of centimetres, incompatible with the assembly and the space constraints. These large deformations would also change the cooling water volume surrounding the target, negatively impacting the moderation process and the resolution function. In addition, this behavior would provoke loss of contact between the lead core and the Ti-6Al-4V layer, making the target cooling largely inefficient.

2.3 Advanced design studies

From the preliminary design stage presented in Sec. 2.1, three target solutions were retained:

- Bare-lead core, cooled by water. Similar to Target #2, but with a flat top to increase neutron flux and resolution in EAR2.
- Bare-lead core with flat top and with Ti-6Al-4V cladding, cooled by water. The Ti-6Al-4V layer avoids direct contact between cooling water and lead, which is then protected from water erosion-corrosion.
- Tantalum-clad tungsten core obtained by hot isostatic pressing, cooled by water and surrounded by a gas-cooled massive lead block.

An additional target concept was added for a total of four solutions examined in the advanced design stage. This new concept is composed of a Ti-6Al-4V-clad lead core, cooled by water and surrounded by a gas-cooled massive lead block.

The mechanical design of the four options considered in this stage can be categorized in the two different concepts shown in Fig. 2.9. The first two solutions are similar to the design of Target #2 and are based on a stainless steel vessel containing a water-cooled lead cylinder ($\varnothing 60$ cm) with a flat top. The only difference between them is the presence of an additional Ti-6Al-4V layer in the second solution, which protects the pure lead core from erosion-corrosion and acts as anti-creep structure. The other two solutions (second concept of Fig. 2.9, on the right) are composed by a water-cooled core absorbing most of the beam energy, surrounded by a gas-cooled massive lead block; the core can be made of tantalum-clad tungsten or pure lead contained in a Ti-6Al-4V protective layer. Both concepts include a water moderator with aluminum alloy casing for each experimental area.

2.3.1 Finite element analyses of the different design solutions

CFD (Computational Fluid Dynamics) and FEM (Finite Element Method) analyses have been performed for Target #2 and for the four Target #3 design solutions presented in this section.

CFD analyses provide estimations of the cooling system parameters such as pressure drop, temperature of the coolant, and heat transfer coefficient (HTC) between the coolant and

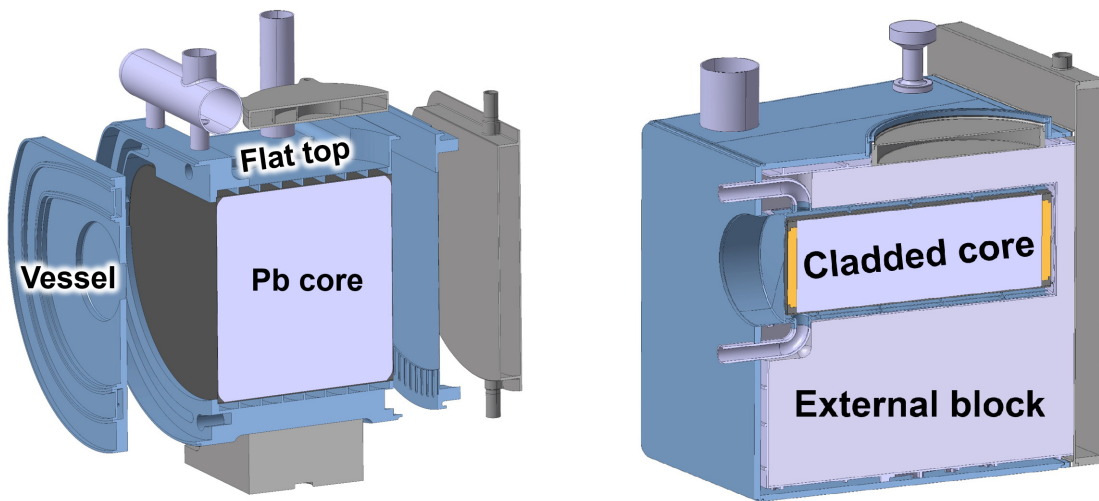


Figure 2.9. The two alternative concepts for the design of Target #3. Left: water-cooled lead cylinder with flat top. Right: water-cooled cladded core with gas-cooled external lead mass [33, 58].

the target surface. The input parameters needed for these analyses are the cooling system geometry, the type of coolant, and the boundary conditions (usually flow rate and/or flow speed at the inlets and the outlets). CFD analyses help designing the cooling system and define its operational parameters, as well as providing the inputs and the boundary conditions for the FEM thermal analyses.

FEM analyses help performing thermo-mechanical calculations aimed at estimating temperature, deformations, stresses, and strains in the target when subjected to proton beam impacts.

Beam parameters

The boundary condition considered as beam load in the FEM thermal analyses is defined as internal heat generation and it is described by the distribution of deposited energy obtained as output from FLUKA Monte Carlo simulations. The four design concepts discussed in this section were compared on the basis of their thermo-mechanical behaviour when impacted by the same beam load. The beam parameters assumed for this stage of the design studies are listed in Table 2.1.

Thermal analyses

For the four considered design solutions, the following thermal simulations have been performed:

- Transient thermal simulation of the first ten supercycles starting from room temperature

Chapter 2. The design studies for the new n_TOF target

(with the actual time structure of the beam as delivered from the Proton Synchrotron).

- Steady-state thermal simulation of the target impacted by the average beam power applied constantly (without time structure).
- Transient thermal simulation of ten supercycles starting from the steady-state condition to estimate the peak temperature once steady state is reached (with time structure).

Table 2.1. Beam parameters assumed for the advanced studies of the n_TOF Target #3 design.

Pulse intensity:	10^{13} p^+
Beam momentum:	$20 \text{ GeV}/c$
Pulse energy:	32 kJ
Pulse length:	25 ns (4σ)
Beam size:	$15 \text{ mm} \times 15 \text{ mm}$ (1σ)
Minimum period between two consecutive pulses:	1.2 s
Supercycle length:	36 s (30 cycles of 1.2 s)
Number of pulses per supercycle:	14 consecutive pulses (15.6 s followed by a 20.4 s cooldown without beam)
Average intensity:	$3.89 \times 10^{12} \text{ p}^+/\text{s}$
Average current:	0.62 μA
Average power:	12.5 kW
Peak current:	91.3 A
Peak power:	1.8 TW

The material properties needed for the thermal simulations (density, thermal conductivity, and specific heat) are taken from Ref. [59] for all the simulated materials. The variation of the thermal properties with temperature is taken into account in the simulations.

A typical evolution of the target temperature is shown in Fig. 2.10, where the evolution of temperature in Target #2 is plotted. It is possible to distinguish the small temperature spikes due to the impact of the single pulses, the larger cycles due to the repetition of the 36-s PS supercycle, and the overall temperature rise approaching asymptotically the steady-state condition. Depending on the design solution considered, the time to reach steady state (time needed to reach 95% of the peak temperature) from 21.5°C ranges between 4 and 15 minutes.

Structural analyses

For all the four design solutions examined, the structural response has been simulated in the two following load cases:

1. First pulse on the target at room temperature.

2. Last of the 14 consecutive pulses in the supercycle at steady state.

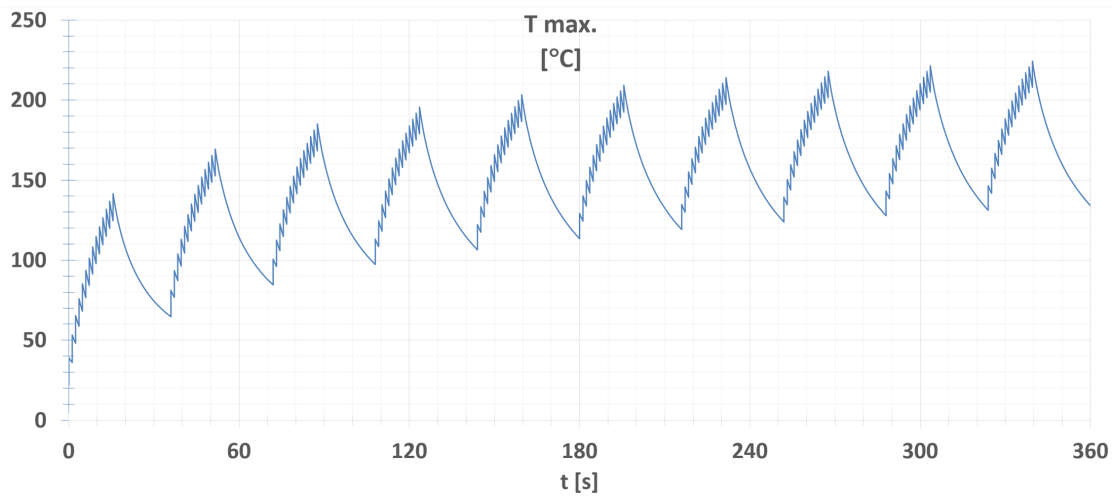


Figure 2.10. Evolution of maximum temperature in the first ten supercycles (Target #2 FEM thermal simulation).

The first load case corresponds to the highest single-pulse temperature spike and, consequently, to the maximum stress caused only by dynamic effects (stress-wave propagation). The second load case corresponds to the maximum stress caused by the sum of the overall temperature rise and the dynamic effects.

For each design solution, the maximum stress is compared to the maximum acceptable stress in the material leading to fatigue failure after 4×10^6 cycles, which is an estimation of the number of supercycles in ten years of operation. Differently, the stress due to dynamic effects only is compared to the maximum acceptable stress leading to fatigue failure after 4×10^7 cycles, which is an estimation of the number of pulses on the target in the same period of ten years. The dynamic effects are caused by the impulsive application of the pulse energy (32 kJ in 25 ns). The impulsive load leads to propagation of elastic stress waves in Ti-6Al-4V, tantalum, and tungsten, and to propagation of plastic stress waves in pure lead. Figure 2.2 shows examples of longitudinal and radial stress wave propagation in lead.

The material properties needed for the FEM structural analyses (density, thermal expansion coefficient, Young's modulus, Poisson's ratio, yield strength, tensile strength, and fatigue strength) for all the materials of interest are taken from [59, 60]. Since the analyses described in the following sections show that lead is stressed beyond its yield strength, the whole stress-strain curve is needed to take the plastic behaviour into account: the data is taken from [61]. The variation of all the material properties with temperature is taken into account in the simulations.

The availability of fatigue data for high purity lead at high temperature and high number of cycles is limited. The reference values used in this work are estimated values at 100°C obtained by extrapolation from the room temperature data provided in [60] and the data at 100°C and

10^7 cycles from [62]. Therefore, when the temperature of pure lead is higher than 100°C , the indicated reference value is overestimating the acceptable fatigue strength for lead. This does not change the conclusions since the analyses described in the following sections show that the fatigue strength at 100°C is already lower than the arising stresses, and the main purpose of this design stage is to compare stress values between the different solutions. Fatigue data for Ti-6Al-4V, tantalum, tungsten, and beryllium is available only for temperatures much higher than the ones reached in this work. Therefore, the acceptable fatigue values for these materials were defined with reference to room temperature data but, conservatively, the lowest value within the fatigue strength range provided is considered. This approach is considered acceptable since the maximum temperatures reached in these materials ($<100^\circ\text{C}$) are very low compared to their melting point and, based on the high temperature data ([59, 60, 63]), the estimated decrease of strength is minimal.

2.3.2 Analysis of the pure lead cylindrical target (Target #2)

The modelled target core is a $\varnothing 60\text{ cm} \times 40\text{ cm}$ pure lead cylinder (Fig. 2.11). The FEM model is composed by 20-node second-order hexahedral elements.

CFD analysis

The parameters used for the CFD simulations are listed in Table 2.2, along with some of the most relevant results (water temperature, pressure drop, and heat transfer coefficient). Figure 2.12 shows the resulting distribution of the heat transfer coefficient and Fig. 2.13 shows the water flow streamlines. There are three inlets to three different cooling circuits, one for each side of the target: proton side, neutron side, and cylindrical side. The three circuits join into one single outlet before leaving the target.

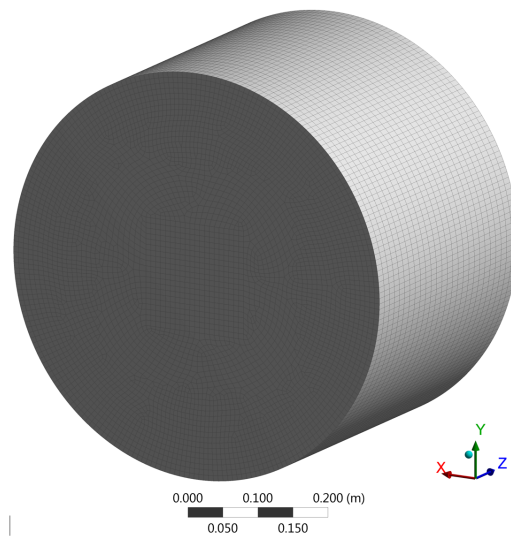


Figure 2.11. FEM model used for Target #2.

Table 2.2. Boundary conditions and results of the CFD simulations for Target #2.

Flow rate:	7 m ³ /h
Cooling water temperature at inlet:	21.5°C
Max. water temperature:	21.6°C
Pressure drop between inlet and outlet:	0.12 bar
HTC range (Fig. 2.12):	170–2500 W/(m ² °C)

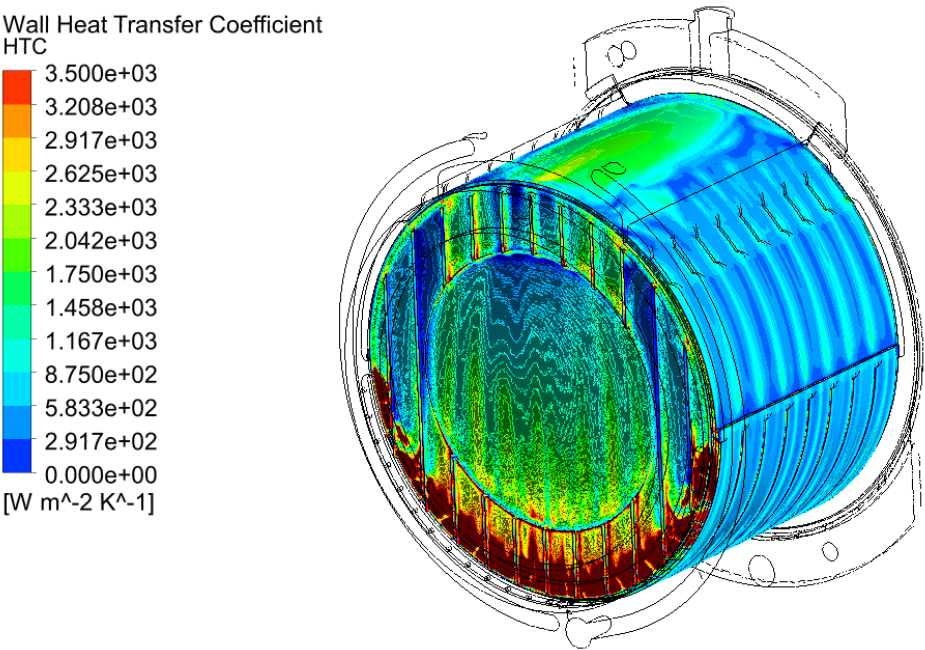


Figure 2.12. Target #2 CFD results: HTC distribution on the surface of the pure lead cylinder.

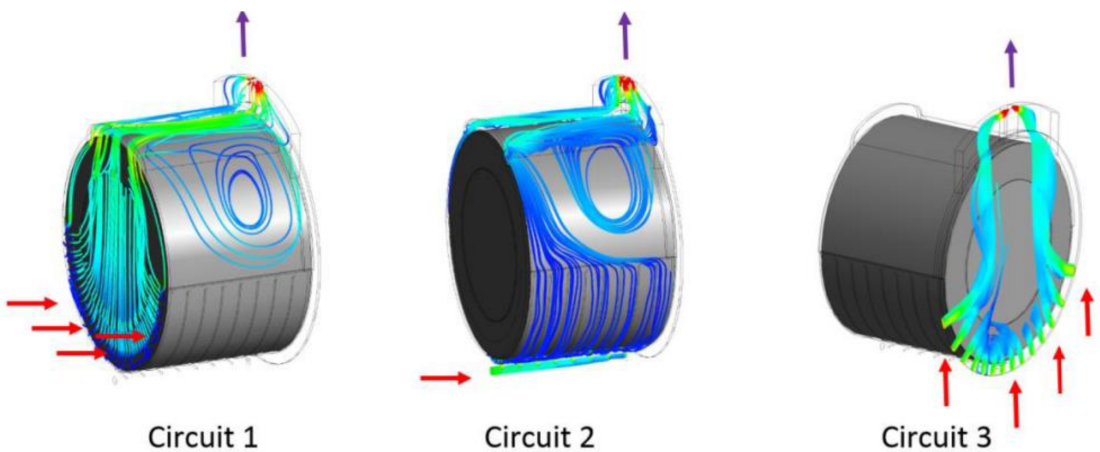


Figure 2.13. Target #2 CFD results: cooling water flow streamlines. There are three inlets to three different cooling circuits, one for each side of the target: proton side, neutron side, and cylindrical side. The three circuits join into one single outlet before leaving the target.

Thermal analysis

For the thermal analysis, the HTC distribution resulting from the CFD simulations was applied to the FEM model in Fig. 2.11 as convective boundary condition. The heat load input is a spatial distribution of heat generation representing the energy absorbed during the beam impact and obtained by FLUKA Monte Carlo simulations, as described in Sec. 2.3.1. Figure 2.14 shows the steady-state temperature distribution in Target #2, while the maximum temperature evolution in the target resulting from transient simulations was already shown in Fig. 2.10. The main results of the FEM thermal simulations of Target #2 are summarized in Table 2.3. As a reminder, the melting temperature of lead is 327°C [62].

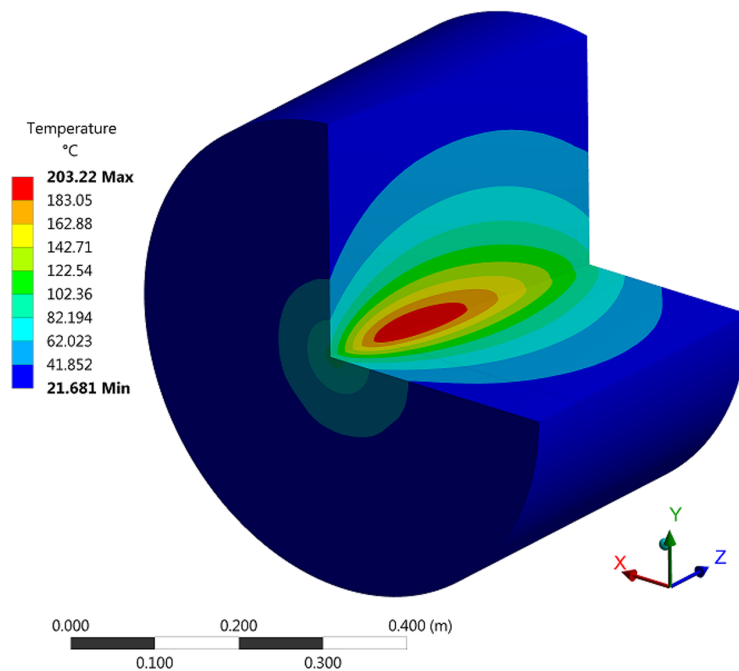


Figure 2.14. Target #2 FEM thermal results: steady-state temperature distribution.

Table 2.3. Results of the FEM thermal simulations for Target #2.

Steady-state max. temperature (Fig. 2.14):	203°C
Max. ΔT due to a single pulse:	17°C
Max. ΔT in one supercycle:	120°C
Peak temperature:	242°C

Structural analysis

The main results of the structural analysis are summarized in Table 2.4. The stress values, especially the maximum tensile stress due to stress-wave propagation, reach high levels for the material under examination. In light of the preliminary analyses performed, occurrence of damage in pure lead during the target's lifetime cannot be excluded.

Table 2.4. Main results of the structural analysis of Target #2.

Max. von Mises stress (quasi-static):	2.0 MPa
Max. principal stress (quasi-static):	2.0 MPa
Max. acceptable fatigue stress (4×10^6 cycles):	1.1 MPa
Max. von Mises stress (dynamic):	2.1 MPa
Max. principal stress (dynamic):	12.0 MPa
Max. acceptable fatigue stress (4×10^7 cycles):	0.6 MPa

2.3.3 Pure lead target with flat top

The modelled target core is a $\varnothing 60 \text{ cm} \times 40 \text{ cm}$ pure-lead cylinder with a horizontal cut 15 cm above the axis (Fig. 2.15). The FEM model is composed by 20-node second-order hexahedral elements.

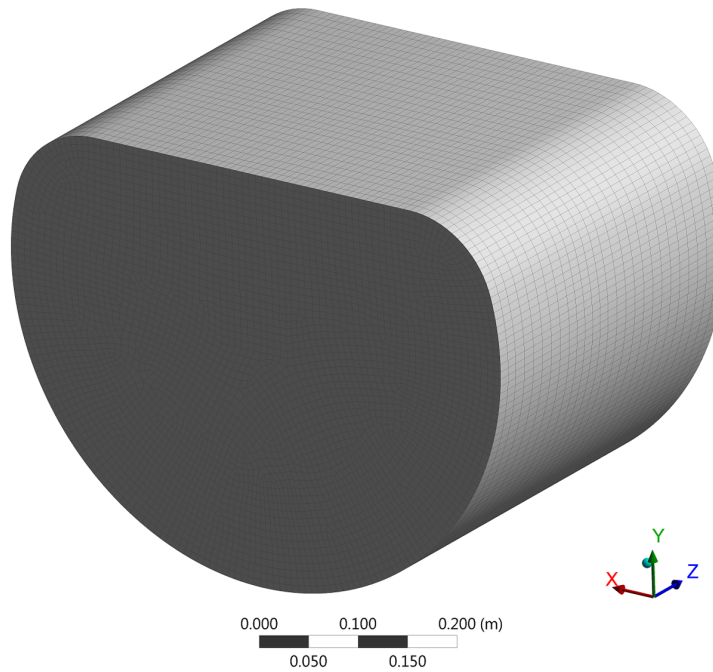


Figure 2.15. FEM model used for the bare-lead solution with flat top.

CFD analysis

The parameters used for the CFD simulations are listed in Table 2.5, along with some of the most relevant results (water temperature, pressure drop, and HTC). Figure 2.16 shows the resulting distribution of HTC and Fig. 2.17 shows the water flow streamlines. There are three inlets to three different cooling circuits, one for each side of the target: proton side, neutron side, and cylindrical side. The three circuits join into one single outlet before leaving the target.

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Table 2.5. Boundary conditions and results of the CFD simulations for the lead solution with flat top.

Flow rate:	7 m ³ /h
Cooling water temperature at inlet:	21.5°C
Max. water temperature:	21.6°C
Pressure drop between inlet and outlet:	0.12 bar
HTC range (Fig. 2.16):	170–2500 W/(m ² °C)

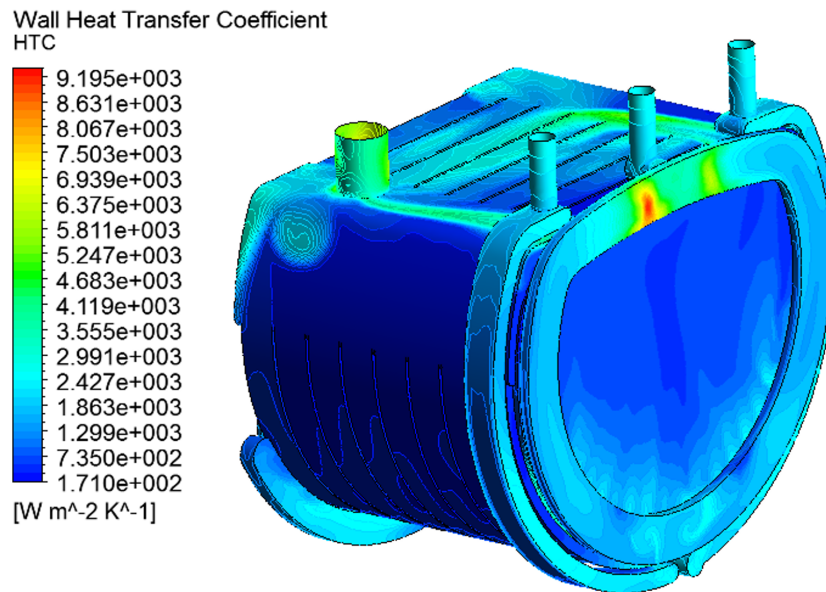


Figure 2.16. CFD results of the bare-lead solution with flat top. HTC distribution on the surface of the pure-lead target core.

Thermal analysis

For the thermal analysis, the HTC distribution resulting from the CFD simulations was applied to the FEM model in Fig. 2.15 as convective boundary condition. The heat load input is a spatial distribution of heat generation representing the energy absorbed during the beam impact and obtained by FLUKA Monte Carlo simulations, as described in Sec. 2.3.1. Figure 2.18 shows the steady-state temperature distribution in this solution. The main results of the FEM thermal simulation are summarized in Table 2.6.

Despite the similarity between the two target concepts examined so far, the temperature reached in this concept (Table 2.6) is slightly lower than in Target #2 (Table 2.3) thanks to the shorter distance between the heat source (the proton beam) and the cooled surface at the top of the target core. This, in addition to the better physics performance in EAR2 (higher neutron flux, better resolution function without 'double peak' thanks to the flat top and the flat moderator, see. Sec. 2.2.2), makes this concept an improved alternative with respect to Target #2.

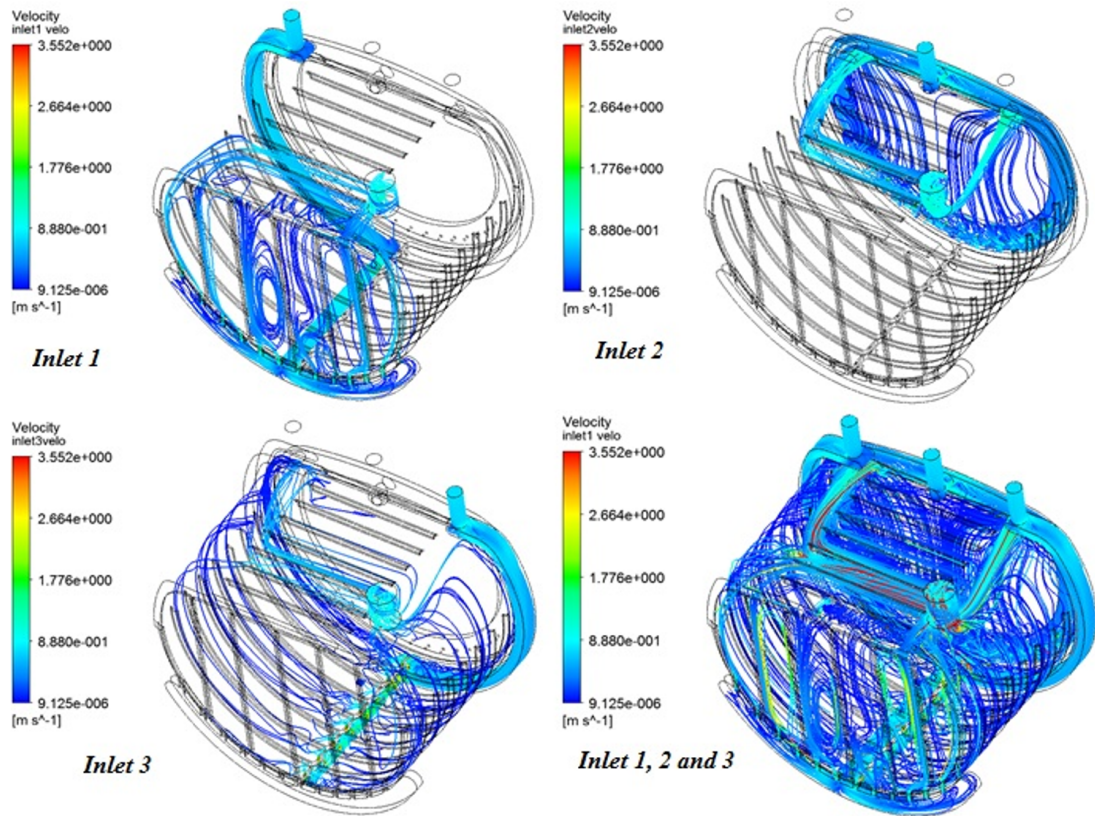


Figure 2.17. CFD results of the bare-lead solution with flat top: cooling water flow streamlines. There are three inlets to three different cooling circuits, one for each side of the target: proton side, neutron side, and cylindrical side. The three circuits join into one single outlet before leaving the target.

Table 2.6. Results of the FEM thermal simulations for the bare-lead solution with flat top.

Steady-state max. temperature (Fig. 2.18):	196°C
Max. ΔT due to a single pulse:	17°C
Max. ΔT in one supercycle:	115°C
Peak temperature:	221°C

Structural analysis

The main results of the structural analysis are summarized in Table 2.7. Due to the similarity between this solution and Target #2, the stress values are alike: they reach high values for pure lead, especially the maximum tensile value due to stress-wave propagation. In this solution with the flat top, the maximum stress is even higher. This can be explained by the shorter distance between the beam axis and the top of the target: the radial stress waves, originated at the beam axis location, are subjected to attenuation and dispersion for a shorter distance before being reflected on the free surface at the top.

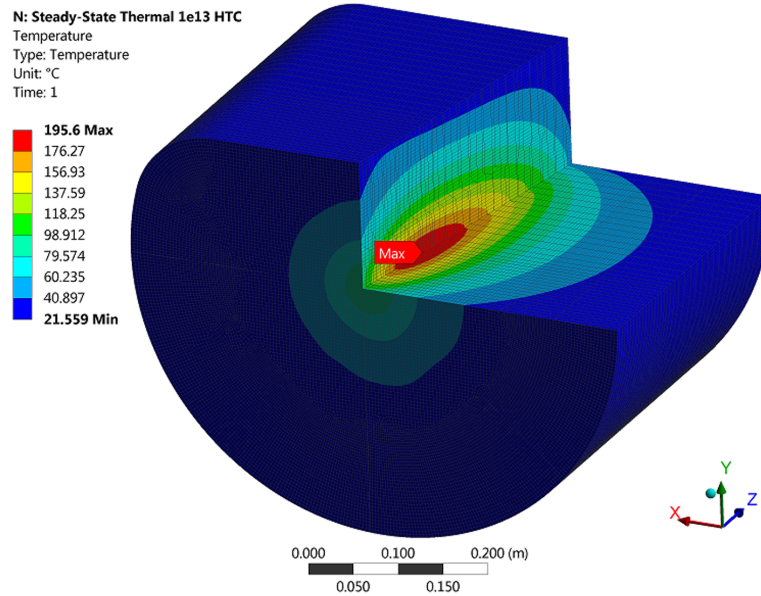


Figure 2.18. FEM thermal results of the bare-lead solution with flat top: steady-state temperature distribution.

Table 2.7. Main results of the structural analysis of the bare-lead solution with flat top.

Max. von Mises stress (quasi-static):	2.0 MPa
Max. principal stress (quasi-static):	2.1 MPa
Max. acceptable fatigue stress (4×10^6 cycles):	1.1 MPa
Max. von Mises stress (dynamic):	2.1 MPa
Max. principal stress (dynamic):	16.3 MPa
Max. acceptable fatigue stress (4×10^7 cycles):	0.6 MPa

2.3.4 Ti-6Al-4V-clad Pb target with flat top

The modelled target core is a $\varnothing 60$ cm $\times$ 40 cm pure lead cylinder with a horizontal cut 15 cm above the axis and contained in a 1-mm thick titanium Grade 5 (Ti-6Al-4V) shell (Fig. 2.19). The lead core is composed by 20-node second-order hexahedral elements whilst the Ti-6Al-4V container is composed by 8-node second-order shell elements. The thermal contact conductance (TCC) between the lead core and the Ti-6Al-4V shell is assumed equal to $1000 \text{ W}/(\text{m}^2 \text{ } ^\circ\text{C})$. This value was estimated with the procedure described in [64], based on the theory described in [65] and [66]. Ti-6Al-4V was selected as container material after a comparison between different candidates (including tantalum, stainless steel AISI 316LN, and Inconel 625). Ti-6Al-4V was selected thanks to its low elastic modulus (leading to lower stress for a fixed deformation), high yield strength (≥ 828 MPa, useful to avoid permanent deformations and loss of contact pressure with the Pb core), and high fatigue strength.

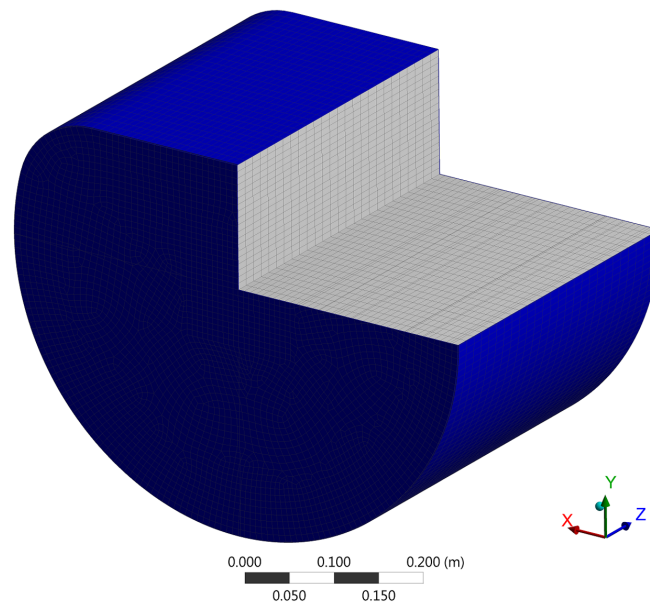


Figure 2.19. FEM model used for the Ti-6Al-4V-clad Pb target.

CFD analysis

Since this solution has the same external geometry of the bare-lead solution with flat top, the same CFD results, described in Sec. 2.3.3, were exploited.

Thermal analysis

Table 2.8 summarizes the main results of the thermal analysis of the Ti-6Al-4V-clad Pb solution with flat top. Figures 2.20 and 2.21 show the steady-state temperature distribution in the lead core and in the Ti-6Al-4V container.

The temperature values reached in this concept (Table 2.8) are higher than in the bare-lead solution (Table 2.6), as expected: the Ti-6Al-4V layer and the interface with the lead core are an additional thermal resistance to the heat flow extracted from the target core. The main advantage of this solution is represented by the protection of the lead core from water erosion-

Table 2.8. Results of the FEM thermal simulations for the Ti-6Al-4V-clad Pb solution with flat top.

	Material	Pb	Ti-6Al-4V
Steady-state max. temperature		206°C	84°C
Max. ΔT due to a single pulse		17°C	3°C
Max. ΔT in one supercycle		115°C	51°C
Peak temperature		253°C	92°C
Melting temperature		327°C	1668°C

corrosion. The temperature reached in the Ti-6Al-4V layer is well within the acceptable limits for this alloy.

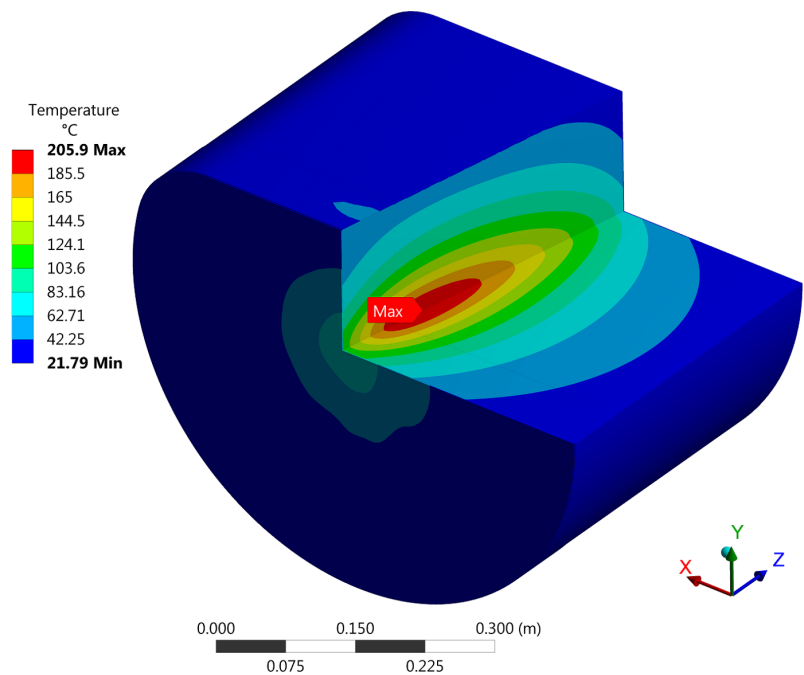


Figure 2.20. FEM thermal results of the Ti-6Al-4V-clad Pb solution with flat top: steady-state temperature distribution in the lead core.

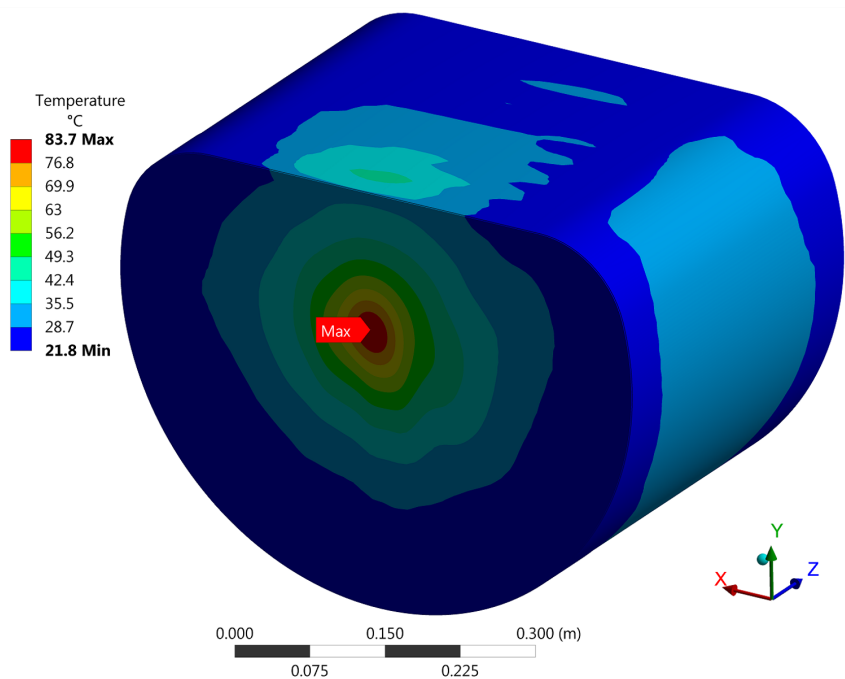


Figure 2.21. FEM thermal results of the Ti-6Al-4V-clad Pb solution with flat top: steady-state temperature distribution in the Ti-6Al-4V container.

Structural analysis

Table 2.9 summarizes the main structural results for the Ti-6Al-4V-clad Pb solution. As expected, the stress values in lead are similar to the bare-lead solution with flat top, although in this case the occurrence of damage in lead is a secondary issue thanks to the Ti-6Al-4V layer supporting the integrity of the core. The stresses induced in the Ti-6Al-4V layer are within the acceptable limits. As explained in Sec. 2.2.6, the main issues with this concept are the higher photon background due to the Ti-6Al-4V layer downstream of the lead core, the challenging manufacturing procedure of the assembly, the uncertainty on the thermal contact conductance at the Ti-Pb interface, and the difficult control of the thin Ti-6Al-4V layer's deformations.

Table 2.9. Main results of the structural analysis of the Ti-6Al-4V-clad Pb solution with flat top.

	Material	Pb	Ti-6Al-4V
Max. von Mises stress (quasi-static)		2.0 MPa	209 MPa
Max. principal stress (quasi-static)		1.6 MPa	220 MPa
Max. acceptable fatigue stress (4×10^6 cycles)		1.1 MPa	285 MPa
Max. von Mises stress (dynamic)		2.1 MPa	23 MPa
Max. principal stress (dynamic)		15.9 MPa	25 MPa
Max. acceptable fatigue stress (4×10^7 cycles)		0.6 MPa	265 MPa

2.3.5 Tantalum-clad tungsten core surrounded by lead

This target concept is shown in Fig. 2.8. The two core parts (tantalum-clad tungsten core and Ti-6Al-4V-clad lead insert) have been simulated separately and the two models are shown in Fig. 2.22. The first model is composed by a $\varnothing 10$ cm $\times$ 25 cm Ta-clad W cylinder, while the second model is composed by a Ti-6Al-4V-clad Pb $\varnothing 10$ cm $\times$ 8 cm cylinder inserted

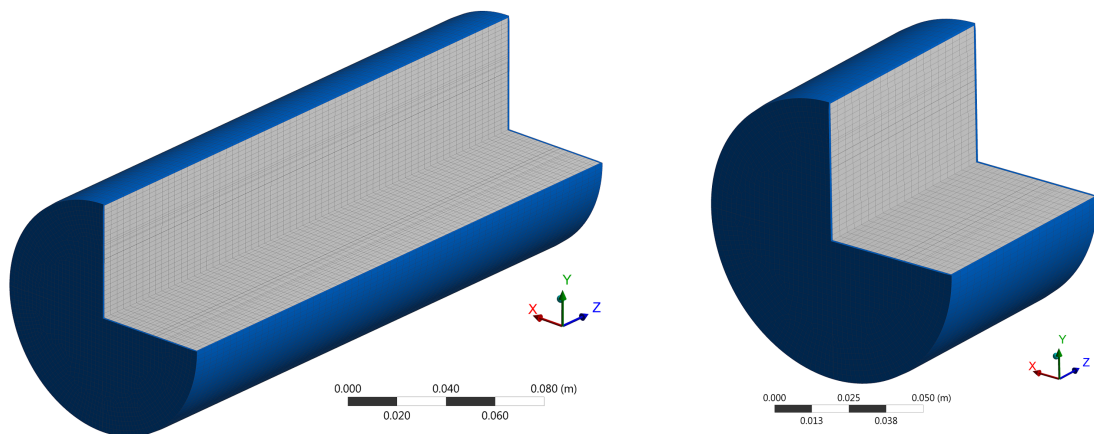


Figure 2.22. FEM model of the tantalum-clad tungsten target core obtained by hot isostatic pressing (left) and of the Ti-6Al-4V-clad lead insert (right).

downstream of the Ta-W core to improve the physics performance (increase neutron flux and reduce background). The tungsten core and the lead insert are composed by 20-node second-order hexahedral elements while the tantalum and the Ti-6Al-4V shells are composed by 8-node second-order shell elements. The thermal contact between tantalum and tungsten is obtained by hot isostatic pressing and it is modelled as a perfect contact (with no thermal resistance at the interface), while the thermal contact conductance between Ti-6Al-4V and lead is assumed equal to $600 \text{ W}/(\text{m}^2 \text{ }^\circ\text{C})$. This value was estimated with the procedure described in [64], based on the theory described in [65] and [66]. The external lead mass shown in Fig. 2.8 is similar to the one of the concept described in Sec. 2.3.6, where the CFD, thermal, and structural analysis of this component are presented.

CFD analysis

This section shows the results of the fluid analysis of the water volume surrounding the Ta-W core in Fig. 2.8. The parameters used for the CFD simulations are listed in Table 2.10, along with some of the most relevant results (water temperature, pressure drop, and heat transfer coefficient). Figure 2.23 shows the resulting distribution of HTC and the water flow streamlines.

Table 2.10. Boundary conditions and results of the CFD simulations for the tantalum-clad tungsten concept.

	Flow rate:	$7 \text{ m}^3/\text{h}$
Cooling water temperature at inlet:		21.5°C
Max. water temperature:		21.6°C
Pressure drop between inlet and outlet:		0.12 bar
HTC range (Fig. 2.23):		$930\text{--}8000 \text{ W}/(\text{m}^2 \text{ }^\circ\text{C})$

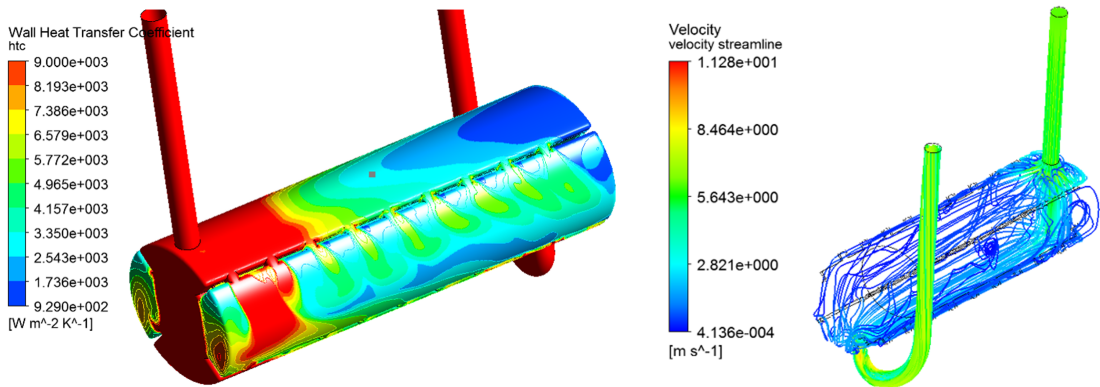


Figure 2.23. CFD results of the tantalum-clad tungsten target solution. Left: heat transfer coefficient distribution on the surface of the tantalum envelope. Right: cooling water flow streamlines.

Thermal analysis

Table 2.11 summarizes the main results of the thermal analysis of the tantalum-clad tungsten solution. Figure 2.24 shows the peak temperature distribution in the tantalum-clad tungsten core and the steady-state temperature distribution in the Ti-6Al-4V-clad lead insert.

Thanks to the water cooling system specifically dedicated to the inner target core, which is the part that absorbs most of the beam energy, the maximum values of temperature in this concept are lower than in the other ones.

Table 2.11. Results of the FEM thermal simulations for the tantalum-clad tungsten target concept with Ti-6Al-4V-clad lead insert and surrounded by lead.

Material	W	Ta	Pb	Ti-6Al-4V
Peak temperature	94°C	54°C	54°C	56°C
Melting temperature	3422°C	3017°C	327°C	1668°C

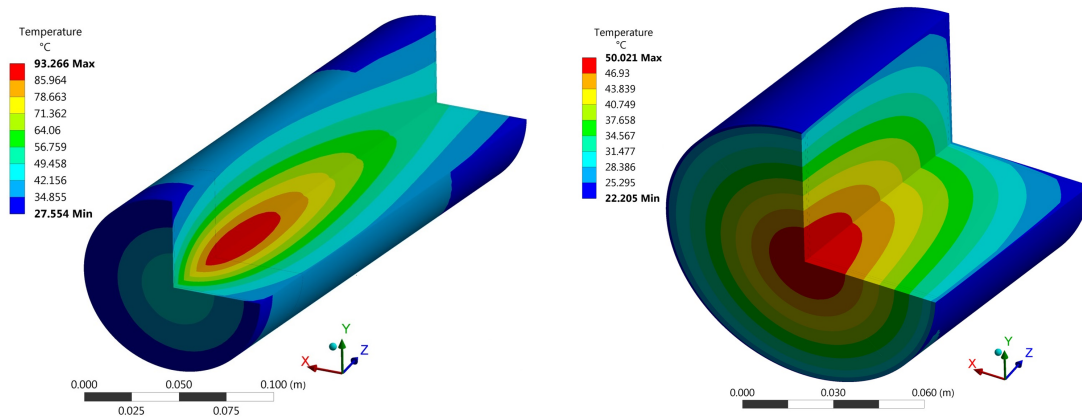


Figure 2.24. FEM thermal results of the tantalum-clad tungsten target concept. Left: peak temperature distribution in the tantalum-clad tungsten core. Right: steady-state temperature distribution in the Ti-6Al-4V-clad lead insert.

Structural analysis

Table 2.12 summarizes the main structural results for the tantalum-clad tungsten target concept. Thanks to the better thermomechanical properties of the materials employed and the lower temperature reached, this solution offers the best response in terms of stress in the target. It has been anyway discarded for the following critical issues:

- Physics performance: lower neutron fluence (75% the one of Target #2 around 1 MeV) and higher background. The reduction in fluence is caused by strong inelastic channels in tungsten.
- Complexity of the assembly: this concept requires two independent cooling circuits

and many parts. The tantalum-clad tungsten core is enclosed in a stainless steel vessel for the water cooling circuit, which is in turn embedded in an external massive lead block. Moreover, an additional Ti-6Al-4V-clad Pb insert is required to improve physics performance (neutron flux and background). Each part adds uncertainty to the long term behaviour of the target and manufacturing complications.

- The need of a Ti-6Al-4V-clad lead insert leads to the same issues described for the Ti-6Al-4V-clad lead solution with flat top of Sec. 2.3.4. It is difficult to manufacture the insert ensuring the value of thermal contact conductance between Ti-6Al-4V and lead assumed by design, especially if required for the entire 10-year lifetime of the target. On the other hand, these issues would be easier to solve for this concept, thanks to the smaller size and the regular shape (i.e. cylindrical) of the Ti-6Al-4V-clad lead part.

Table 2.12. Main results of the structural analysis of the tantalum-clad tungsten target concept with Ti-6Al-4V-clad lead insert and surrounded by lead.

	Material	W	Ta	Ti-6Al-4V
Max. von Mises stress		81 MPa	32 MPa	129 MPa
Max. principal stress		68 MPa	32 MPa	176 MPa
Max. acceptable fatigue stress (4×10^6 cycles)		480 MPa	43 MPa	285 MPa
Max. acceptable fatigue stress (4×10^7 cycles)		425 MPa	37 MPa	265 MPa

2.3.6 Ti-6Al-4V-clad lead core surrounded by a massive lead block

As introduced in Sec. 2.3, also this target concept is composed by a cylindrical core part surrounded by an external lead mass as shown on the right of Fig. 2.9. In this case, the core part is a Ti-6Al-4V-clad lead cylinder, while the external mass is made from pure lead. The Ti-6Al-4V-clad lead core part and the external lead mass have been simulated separately, with two different FEM models. The first model is composed of a water-cooled, $\varnothing 15$ cm $\times$ 30 cm Ti-6Al-4V-clad lead core with beryllium inserts (Fig. 2.25); the second model is composed of an air-cooled external lead block (Fig. 2.26). The lead parts, the beryllium inserts, and part of the Ti-6Al-4V lid are modelled by 20-node second-order hexahedral elements, while the Ti-6Al-4V is modelled by 8-node second-order shell elements. The Ti-6Al-4V shell thickness is 0.5 mm at the lids and 1.5 mm at the cylindrical surface. The Ti-6Al-4V lids cannot be thicker than 0.5 mm without increasing the background to unacceptable levels. The beryllium inserts are added to provide bending stiffness to the lids and avoid large deformations of the thin 0.5-mm Ti-6Al-4V lids. The different parts (lead cylinder, beryllium inserts, and Ti-6Al-4V envelope) are in mechanical contact at their interfaces and the thermal contact conductance between them is assumed equal to $1000 \text{ W}/(\text{m}^2 \text{ }^\circ\text{C})$. This value was estimated with the procedure described in [64], based on the theory described in [65] and [66]. Compared to the Ti-6Al-4V-clad lead solution with flat top of Sec. 2.3.4, the Ti-6Al-4V-clad lead part can be perfectly cylindrical and much smaller ($\varnothing 15$ cm $\times$ 30 cm), thus reducing the manufacturing and assembling issues.

The details on the mechanical design of this part and the manufacturing of a prototype are presented in Chap. 4.

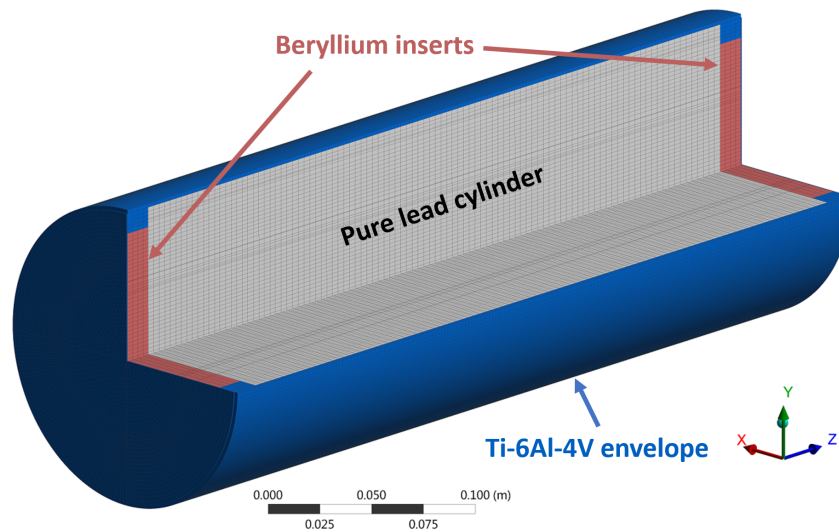


Figure 2.25. FEM model of the Ti-6Al-4V-clad lead core. The beryllium inserts are added to provide bending stiffness to the lids and avoid large deformations of the thin 0.5-mm Ti-6Al-4V lids.

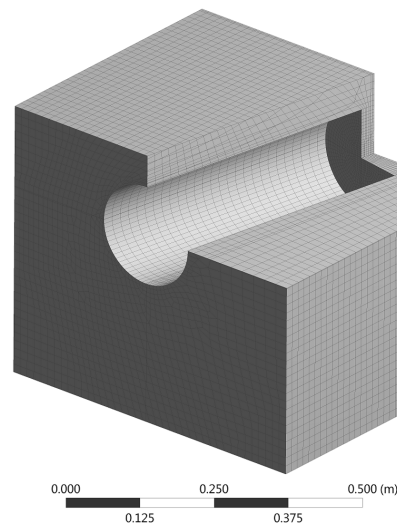


Figure 2.26. FEM model of the external lead mass surrounding the Ti-6Al-4V-clad lead core shown in Fig. 2.25.

CFD analysis

Table 2.13 summarizes the main cooling parameters of this solution. The water circuit has the purpose of cooling the Ti-6Al-4V-clad lead core, while the air circuit has the purpose of cooling down the external lead mass. Figures 2.27 and 2.28 show the heat-transfer-coefficient map and the flow streamlines of the water cooling system for the Ti-6Al-4V-clad lead core.

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Figures 2.29 and 2.30 show the heat-transfer-coefficient maps and the flow streamlines of the air cooling system for the external lead mass.

Table 2.13. Boundary conditions and results of the CFD simulations for the water-cooled Ti-6Al-4V-clad lead core solution surrounded by an air-cooled lead mass.

	Water	Air
Flow rate	4.9 m ³ /h	50 m ³ /h
Cooling water temperature at inlet	21.5°C	21.5°C
Max. fluid temperature	23.1°C	82°C
Pressure drop between inlet and outlet	0.8 bar	37 Pa
HTC range (Fig. 2.23)	230–30000 W/(m ² °C)	2.6–40 W/(m ² °C)

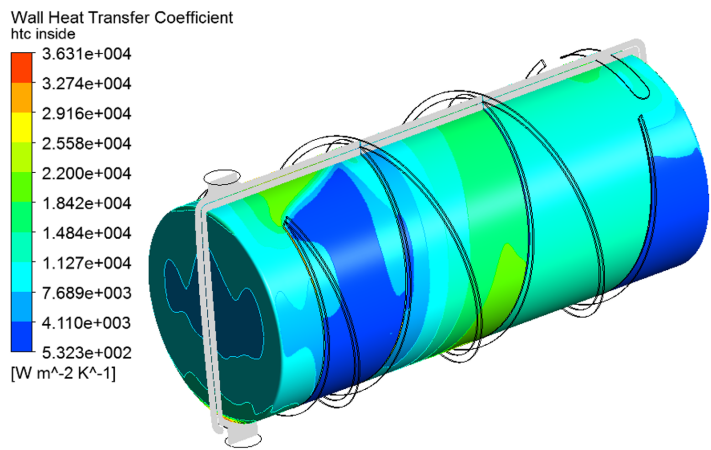


Figure 2.27. CFD results of the Ti-6Al-4V-clad lead target solution: HTC distribution on the surface of the Ti-6Al-4V envelope.

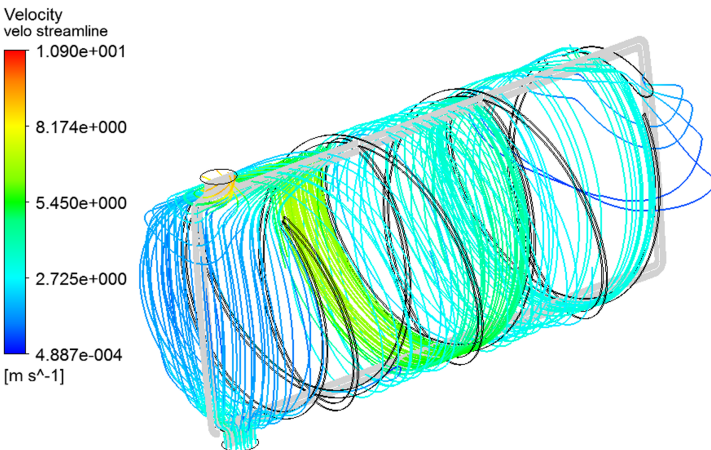


Figure 2.28. CFD results of the Ti-6Al-4V-clad lead target solution: cooling water flow streamlines.

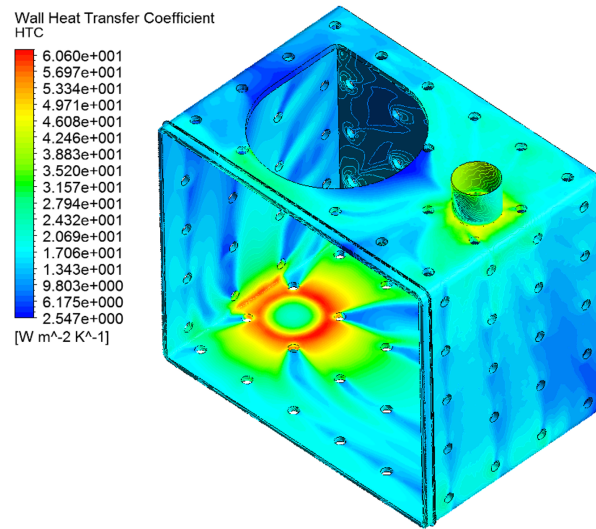


Figure 2.29. CFD results of the Ti-6Al-4V-clad lead target solution: HTC distribution of the air-cooled lead external block.

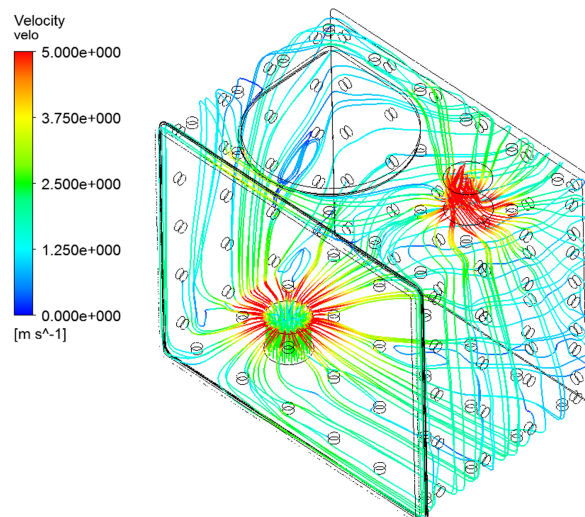


Figure 2.30. CFD results of the Ti-6Al-4V-clad lead target solution: Cooling air flow streamlines.

Thermal analysis

Table 2.14 summarizes the main results of the thermal analysis of the Ti-6Al-4V-clad lead solution with beryllium inserts (model in Fig. 2.25) and surrounded by an external lead mass (model in Fig. 2.26). Figure 2.31 shows the steady-state temperature distribution in the Ti-6Al-4V-clad lead core, while Fig. 2.32 shows the steady-state temperature distribution in the external air-cooled lead block.

Thanks to the water cooling system specifically dedicated to the inner target core, which is the part that absorbs most of the beam energy, the maximum values of temperature in this

Chapter 2. The design studies for the new n_TOF target

Table 2.14. Results of the FEM thermal simulations for the Ti-6Al-4V-clad lead target concept with beryllium inserts (model in Fig. 2.25) and surrounded by lead (model in Fig. 2.26).

	Material	Pb (core)	Ti-6Al-4V	Be	Pb (external)
Steady-state max. temperature		160°C	41°C	49°C	137°C
Max. ΔT due to a single pulse		17°C	0.7°C	0.03°C	4°C
Max. ΔT in one supercycle		142°C	6.4°C	32°C	34°C
Peak temperature		217°C	44°C	52°C	151°C
Melting temperature		327°C	1668°C	1287°C	327°C

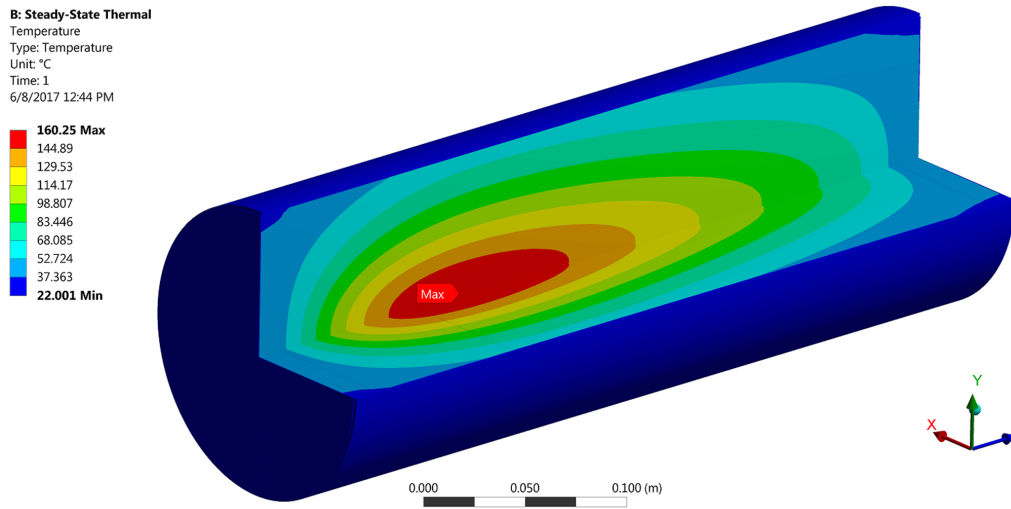


Figure 2.31. FEM thermal results of the Ti-6Al-4V-clad lead target core with beryllium inserts: steady-state temperature distribution.

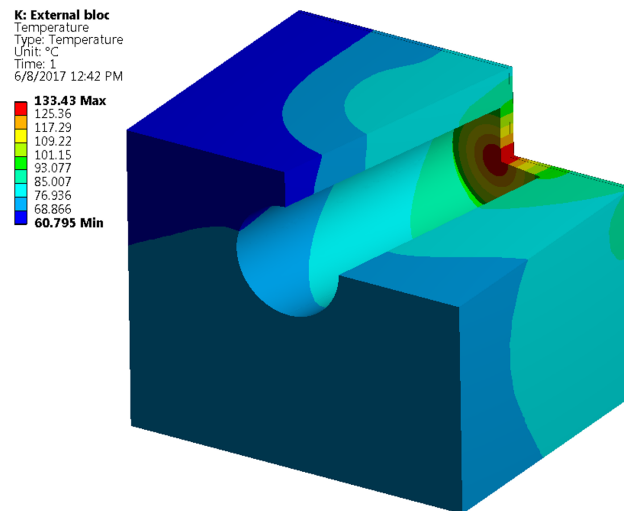


Figure 2.32. FEM thermal results of the external lead mass surrounding the Ti-6Al-4V-clad lead core shown in Fig. 2.31: steady-state temperature distribution.

concept are lower than the ones in Table 2.8.

The power dissipated through the lids of the core cylinder in this solution is only about 15% of the total. Therefore, unlike the solution described in Sec. 2.3.4 (Ti-6Al-4V-clad lead solution with flat top), this solution is valid even if the thermal contact at the lids is lost and the heat is dissipated only through the cylindrical interface between Ti-6Al-4V and lead.

Structural analysis

Table 2.15 summarizes the main structural results for the Ti-6Al-4V-clad lead concept with beryllium inserts (model in Fig. 2.25) and external lead mass (model in Fig. 2.26). The external mass of lead is subjected to lower stresses compared to the other cases, but still above the reference limit values. The maximum stress values of the other materials are within the acceptable fatigue limits. Further details on the thermomechanical behavior of the Ti-6Al-4V-clad lead core with beryllium inserts (model in Fig. 2.25) and on a test under beam irradiation are given in Chap. 4.

Table 2.15. Main results of the structural analysis of the Ti-6Al-4V-clad Pb solution with beryllium inserts (model in Fig. 2.25) and surrounded by an external lead mass (model in Fig. 2.26).

Material	Ti-6Al-4V	Be	Pb (external)
Max. von Mises stress (quasi-static)	230 MPa	161 MPa	1.8 MPa
Max. principal stress (quasi-static)	266 MPa	150 MPa	2.3 MPa
Max. acceptable fatigue stress (4×10^6 cycles)	285 MPa	230 MPa	1.1 MPa
Max. von Mises stress (dynamic)	24 MPa	20 MPa	2.0 MPa
Max. principal stress (dynamic)	28 MPa	15 MPa	3.0 MPa
Max. acceptable fatigue stress (4×10^7 cycles)	265 MPa	220 MPa	0.6 MPa

2.3.7 Conclusions on the advanced design studies

Despite the better thermomechanical response and operational flexibility, the lower physics performance (in terms of instantaneous neutron fluence and background) and high complexity of the assembly led to the exclusion of the tantalum-clad tungsten solution. The remaining three solutions are all lead based. The high stress values in lead are a secondary issue for the clad solutions: this led the review panel of the *Preliminary Design Review* (Fig. 2.1) to recommend holding the same average intensity limit of Target #2 for the bare-lead solution ($1.67 \times 10^{12} \text{ p}^+/\text{s}$), while allowing for a higher average intensity for the two remaining Ti-6Al-4V-clad lead solutions.

The two lead-based solutions with Ti-6Al-4V cladding were then retained for further analysis. An additional concept, based on a variation of the bare-lead solution, was also considered and is described in detail in Chap. 3. This solution is based on nitrogen gas cooling to remove the issues related to water corrosion. Moreover, the fatigue strength of lead in absence of oxygen, at room temperature and 4×10^7 cycles, is 2.3 times the one in air [62, 67]. This is an added

factor in favor of this solution, although the magnitude of the improvement is not known at higher temperatures. The lower cooling capacity of nitrogen gas, as compared to water, is compensated by increasing the surface exposed to the coolant: this is obtained by dividing the lead core in six slices and let the nitrogen flow between them (Fig. 2.33). A structure made of aluminum alloy (EN AW-6082) supports the lead slices in case of damage or creep. This solution would still be subjected to the average intensity limit of $1.67 \times 10^{12} \text{ p}^+/\text{s}$.

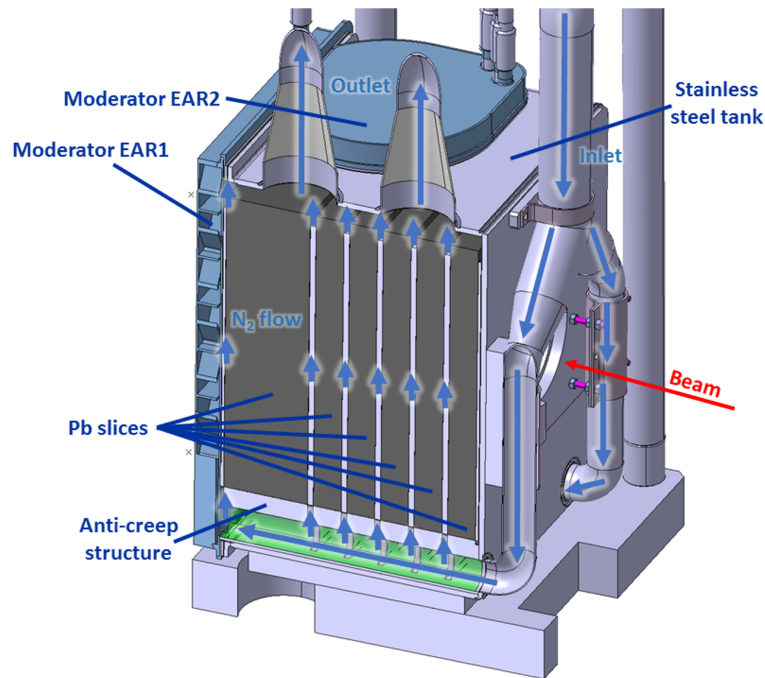


Figure 2.33. Nitrogen-cooled concept (section). Six lead slices are cooled by a forced flow of nitrogen gas. A structure made of aluminum alloy (EN AW-6082) supports the lead slices in case of damage or creep.

Figure 2.34 shows a comparison of the EAR1 neutron fluence for the three concepts considered in this final stage (with Target #2 as reference). The time during which Target #3 would be irradiated by an average intensity significantly higher than $1.67 \times 10^{12} \text{ p}^+/\text{s}$ was estimated to be 10% of the target lifetime. This amount did not justify the lower physics performance (Fig. 2.34) and the higher complexity of the Ti-6Al-4V-clad Pb solutions. This led the review panels of the *Intermediate Engineering Design Review* and *Internal Design Review* (Fig. 2.1) to encourage the adoption of the nitrogen-cooled lead concept, which is the solution of choice for Target #3 and is described in detail in Chap. 3 and in [41].

Moreover, a Ti-6Al-4V-clad Pb prototype (from the design concept in Fig. 2.25) and a small-scale bare-lead prototype in nitrogen atmosphere (from the design in Fig. 2.33) were subjected to a test under beam irradiation. The description of the two tests is provided in Chap. 4.

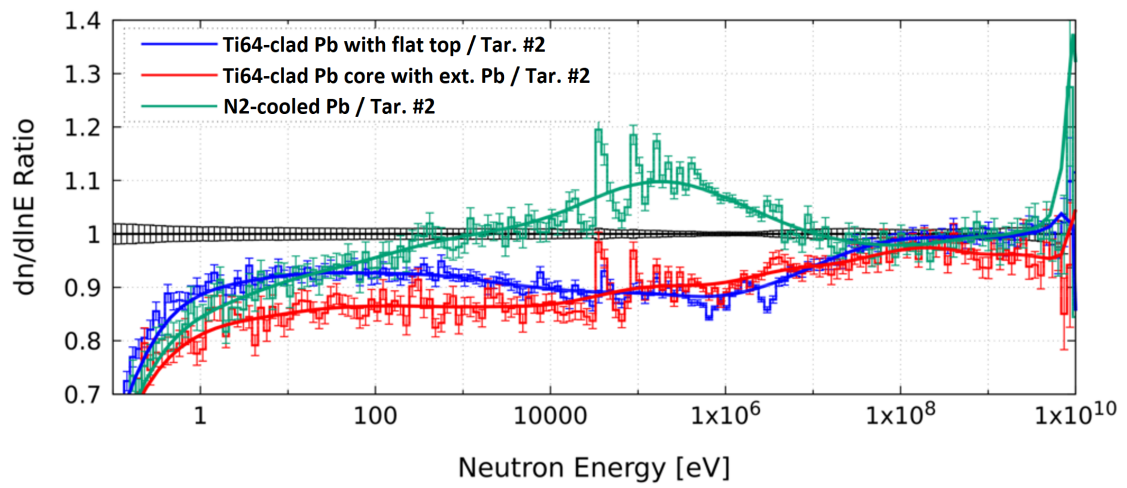


Figure 2.34. EAR1 neutron fluence for the three most promising design concepts, compared to Target #2.

3 The third-generation n_TOF neutron spallation target

3.1 Introduction

The new third-generation spallation target (Target #3) has been installed during the Long Shutdown 2 (LS2), a three-year stop of the CERN accelerators, with the objective of starting operation in 2021. As mentioned in the previous chapters, high-purity lead has been kept as core material owing to its superior performances in terms of reduced photon background with respect to other spallation materials, thanks to its very low neutron capture cross-sections (see Sec. 2.2.4).

Target #3 was designed with the assumption of a beam momentum of 20 GeV/c, with a maximum number of protons per pulse equal to 10^{13} (equivalent to a pulse kinetic energy of 32 kJ). The minimum pulse period is 1.2 s and the maximum average intensity allowed is 1.67×10^{12} p⁺/s, corresponding to an average power on target of 5.4 kW. With a pulse duration of 7 ns (1σ), the peak beam power is 1.8 TW. The beam size on target is assumed equal to 15 mm (1σ).

3.2 Mechanical design

The new target assembly is shown, in exploded view, in Fig. 3.1 [41]: housed inside a stainless steel pressurized vessel, six lead slices are cooled by gaseous nitrogen and are supported by anti-creep plates. These are made from aluminum alloy and include the channels through which the cooling fluid flows. The cooling gas is distributed through two main arteries inside a cradle made from aluminum alloy, which supports the lead core from below. Connected to the vessel, two moderator containers, made from aluminum alloy, are positioned on the path of the neutrons directed towards the two experimental areas. The bond between the stainless steel vessel and the aluminum moderator is obtained by an explosive-bonded joint (with aluminum and titanium interlayers). The lead slices are 5-cm thick, with the exception of the slice close to the EAR1 moderator, which is 15-cm thick. These values were selected to obtain a reasonable compromise between the total target length and lead surface exposed to

the coolant. FLUKA simulations showed a conspicuous reduction in γ -ray background and an increase in neutron flux by merging the 15 cm of lead closest to the EAR1 moderator into a single slice. Figure 3.2 shows a photo of the target core inside the stainless steel vessel before the proton side of the vessel was welded on to close it.

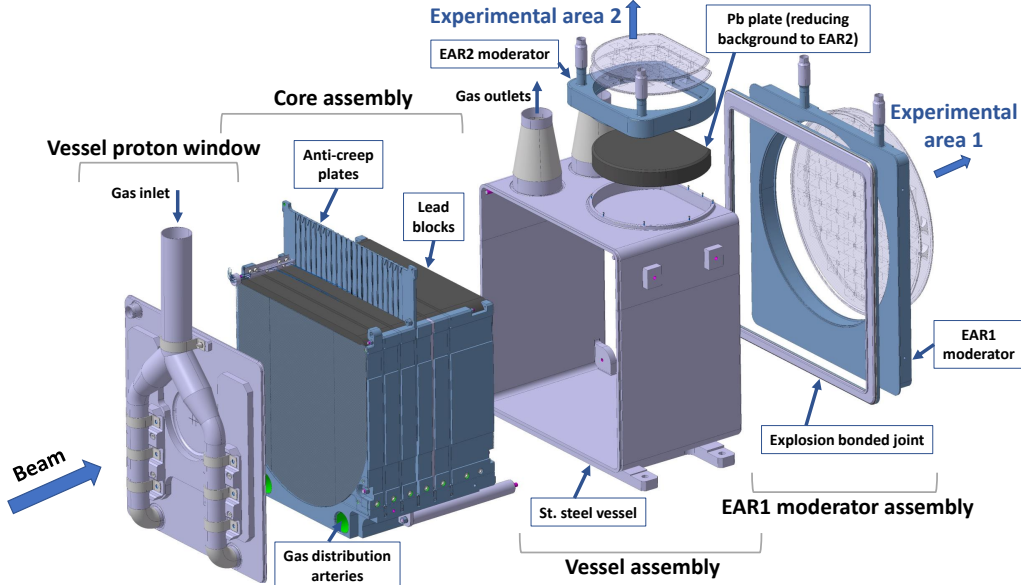


Figure 3.1. Exploded model of Target #3 [41]. The cooling nitrogen gas flows through the channels machined into the anti-creep plates. The inner core is enclosed in an AISI 316L stainless steel vessel. The two moderators are in aluminum EN AW-5083 H112. The EAR1 moderator is bonded to the stainless steel vessel by a bimetallic transition obtained by explosive bonding.

3.2.1 Lead core and anti-creep structure

The main target core is composed of six slices of high-purity lead supported by an aluminum (EN AW-6082 T6) structure that includes anti-creep plates between the slices (Fig. 3.1). The lead grade is UNS L50006, with a minimum purity of 99.98 wt%. The anti-creep aluminum structure also plays a determinant role in the gas distribution thanks to channels machined to distribute optimally the nitrogen gas between the lead slices (see Sec. 3.4.1).

To ensure a correct assembly of the anti-creep plates between the lead slices, the gap between them must be within 45 μm and 195 μm . The minimum value takes the thermal expansion of the lead slices during operation into account, while the maximum value is required to avoid any negative impact on the nitrogen flow. This requirement entails the anti-creep plates to be manufactured with tight dimensional tolerances with respect to thickness (9.85 ± 0.05 mm) and tight geometrical tolerances (flatness lower than 1 mm). The large size of the plates (0.6 m $\times$ 0.6 m) made this requirement particularly difficult to keep while milling the channels, since each milling step can bring distortions to the plate. The accumulation of deformations along the same direction was avoided by changing the side of the plate after each milling step.

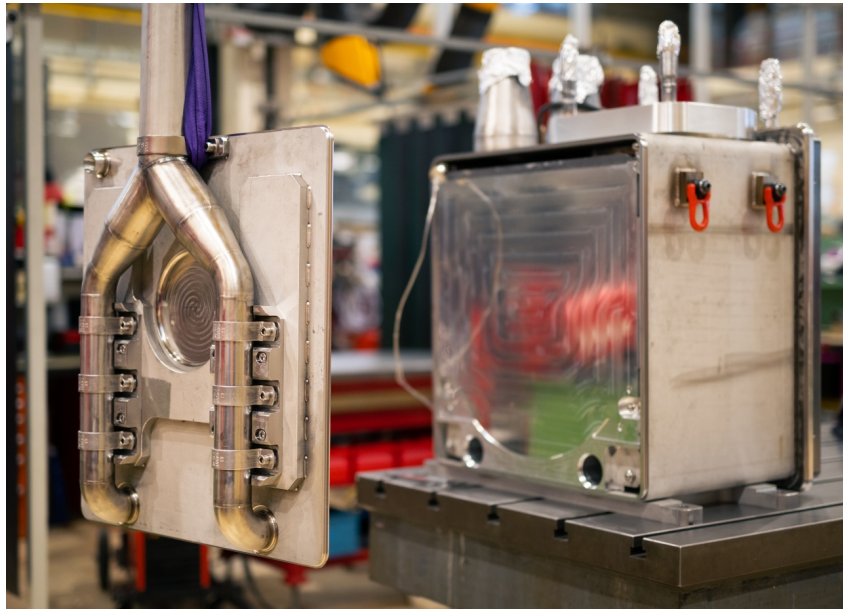


Figure 3.2. Photo of the n_TOF Target #3 core inside the stainless steel vessel before closing the proton side of the vessel by TIG (Tungsten Inert Gas) welding.

Furthermore, a dedicated vacuum table holding the plates during the milling procedure was manufactured, and the whole procedure was tuned and tested by first building a prototype of the plate.

3.2.2 Design of the vessel and moderators

The target core is contained in a 10-mm thick stainless steel (AISI 316L) vessel designed to hold a nominal nitrogen pressure of 0.5 bar. Made by first welding two u-shaped parts, the upstream side is closed by a plate equipped with the nitrogen inlet pipes, welded once the target core was inserted (Fig. 3.1). A beam window was machined at the beam impact area by locally reducing the vessel thickness down to 3 mm to avoid significant heat dissipation due to the interaction between the proton beam and the vessel. An additional stainless steel neutron window (4-mm thick) was welded by electron beam to the top of the vessel and supports a lead plate that reduces the γ -ray background in EAR2, as described in Sec. 3.3.3. The two moderators are connected to two independent water circuits at a nominal pressure of 2.5 bar. They are made from forged aluminum EN AW-5083 H112. This alloy was chosen for its good mechanical properties, their stability after welding, good general corrosion resistance, and the ability to withstand the stresses induced by nitrogen pressure and thermal gradients. The EAR2 moderator is located outside the vessel, placed on top of the 5-cm lead plate above the target core. The moderator is bolted to the vessel and sealed at the top edge to prevent moisture building up between it and the lead plate.

The EAR1 moderator, the larger of the two, was manufactured by deep-milling technology,

which reduced the number of welds needed but required a rigorous production-process qualification to ensure the necessary dimensional tolerances. This moderator is an integral part of the vessel. The transition between the aluminum alloy (EN AW-5083 H112) of the moderator and the stainless steel vessel (AISI 316L) is a rectangular-shaped strip cut out from an explosive-bonded plate. The transition includes two additional ductile layers of pure aluminum (EN AW-1050A H14) and pure titanium (Grade 1) to ensure the good quality of the explosive bonding process (Fig. 3.3). The bond was subjected to helium leak tests and a dye penetrant inspection was performed in accordance with the EN 10228-2 standard on 100% of the machined surfaces. Ultrasonic tests were carried out for each explosive-bonded interface according to EN 10288-4, along with metallographic inspections to validate the quality of the bond.

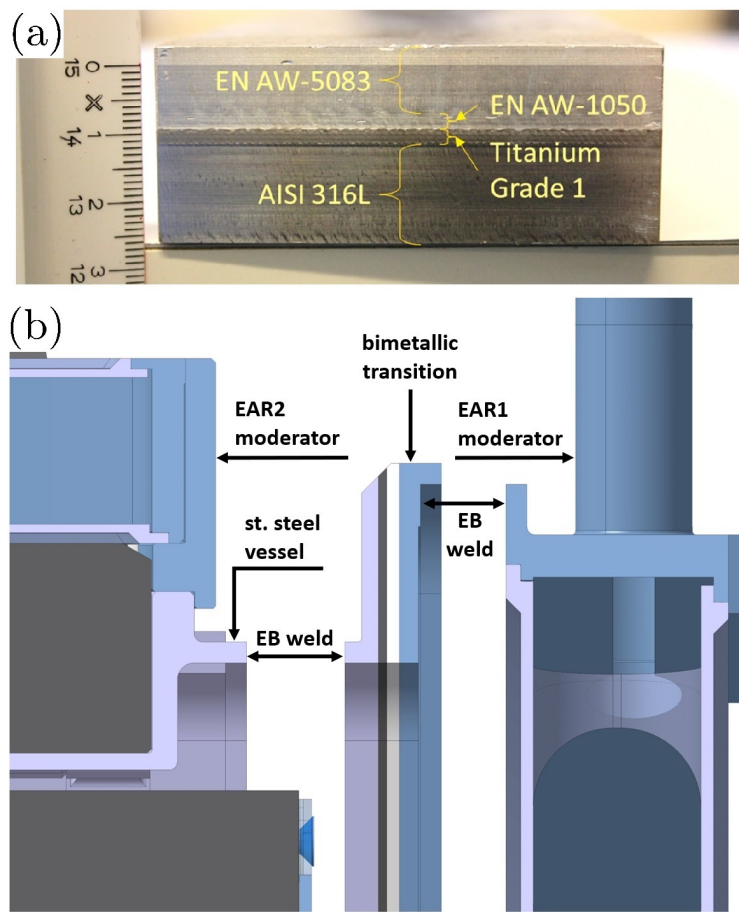


Figure 3.3. (a) Cross-cut of the explosive-bonded bimetallic transition between the stainless steel target vessel and the aluminum EN AW-5083 H112 EAR1 moderator. (b) Schematic view of the explosive-bonded vessel-moderator connection.

In addition to the nondestructive examinations, tensile tests and post-weld metallographic investigations were carried out on representative samples extracted from the original explosive-bonded plate. The tensile tests confirmed a bond strength of 105 MPa, higher than minimum acceptable value of 80 MPa and limited by the strength of the weakest base material, aluminum

EN AW-1050A H14 (Fig. 3.4). The post-weld metallographic investigations confirmed that, after electron-beam welding the explosive-bonded joint to the moderator, the Heat-Affected-Zone (HAZ) is confined far from the interfaces of the bimetallic transition within a safe distance of 3 mm, and thus it does not affect them.

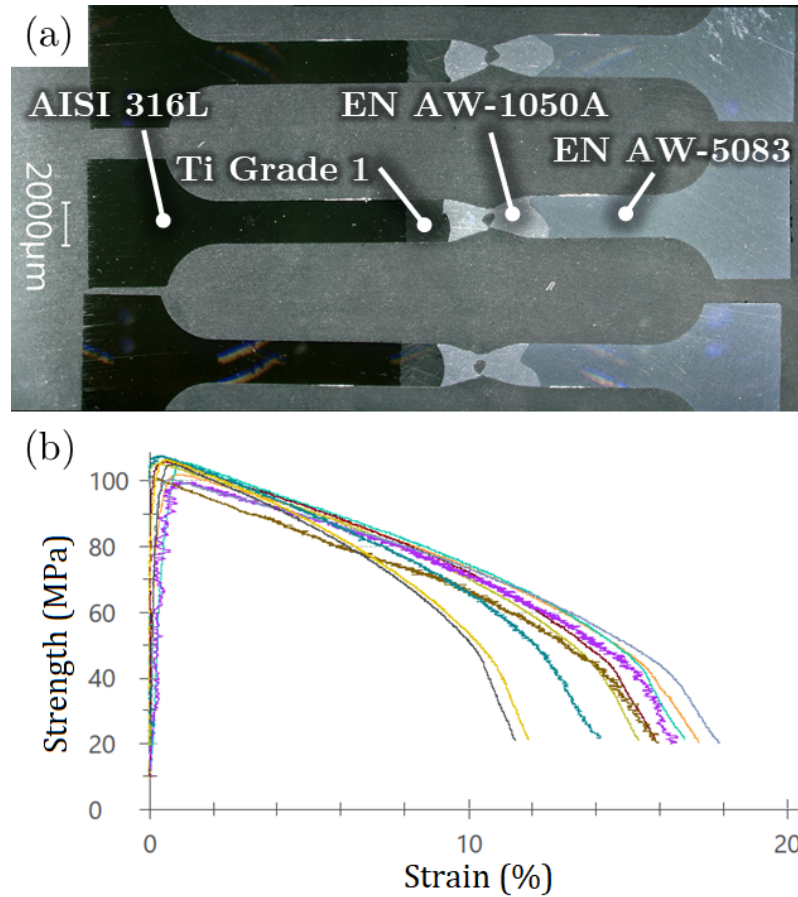


Figure 3.4. (a) Bimetallic-transition specimens tested in tension: for all of them, the interfaces between the different materials of the transition (stainless steel AISI 316L, titanium Grade 1, aluminum EN AW-1050A H14, aluminum EN AW-5083 H112) were stronger than the weakest base material (pure aluminum EN AW-1050A H14). (b) Stress-strain curves resulting from the tensile tests: the ultimate bond strength is 105 MPa.

A first prototype of the explosive-bonded joint, 3-mm thick, failed the leak validation. A second prototype was built to find a safe thickness value for the joint: the prototype was designed to easily perform leak tests and reduce thickness by milling. After each leak test, the thickness of the prototype was reduced in steps of 5 mm, starting from 28 mm and down to 8 mm: no leak was detected at any iteration. It has been concluded that, rather than its thickness, the main factor determining the soundness of a leak-tight joint is the choice of the region of the original plate from where the final joint is extracted. Regions that appear sound after preliminary dye-penetrant and ultrasonic inspections are the best candidates. The final product was selected on this basis, with a final joint thickness of 25 mm, the maximum permitted by assembly and

space constraints.

The EAR1 moderator has been obtained starting from a short cylindrical vessel (Fig. 3.5). The two flat end surfaces, each 3 mm thick, would exceed the maximum acceptable deformations and stresses induced by the 2.5 bar pressure without additional stiffening elements. The use of a precise deep-milling manufacturing technique offered the possibility to add such stiffeners while preserving the monolithic nature of the part and avoiding welds, which would increase failure risks. Up to 80% of the material was removed from a 3D-forged aluminum EN AW-5083 H112 disk, with the remaining 20% shaped to obtain deformations and stresses compliant with the specification. The resulting monolithic center part of the moderator was then welded to the outer housing by electron-beam welding. The outer housing includes the interface with the explosive-bonded joint. To complete the qualification process of the EAR1 moderator, vacuum and pressure tests were successfully carried out to ensure the compliance with pressure vessel safety standards.

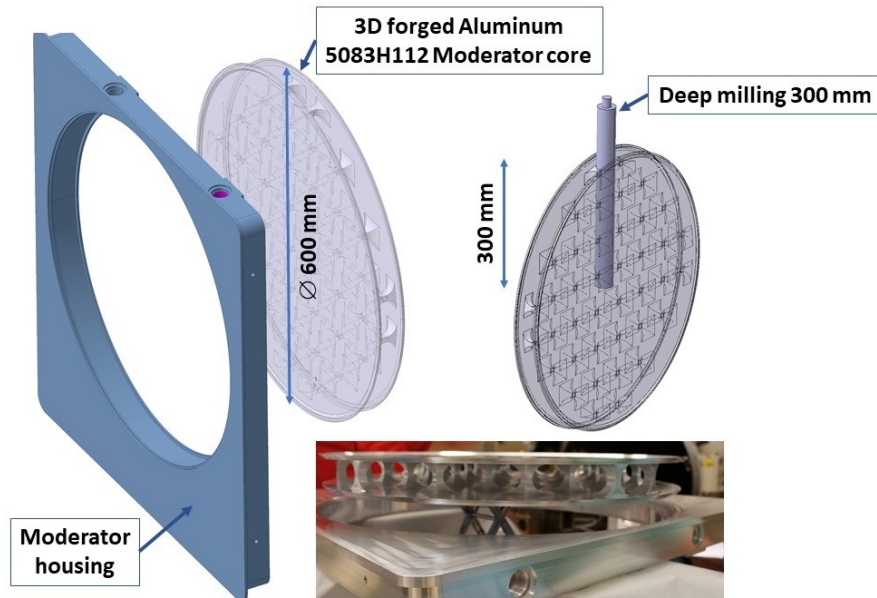


Figure 3.5. Schematic view of the deep milling procedure for the EAR1 moderator manufacturing. The central part is entirely machined from a single solid aluminum block (EN AW-5083 H112). It is then bonded to the housing via electron-beam welding.

3.3 Physics reach

The design of Target #3 aims to further expand the measuring capabilities of the facility [40]. The combination of a high-energy and high-intensity proton beam, long flight paths, specifically designed optical elements along the beamlines, and the optimized spallation target result in high quality neutron beams reaching the experimental areas. The main features of the facility with the new Target #3 are summarized in Table 3.1.

Extensive Monte Carlo studies, performed by means of the FLUKA simulation package [43–46], were conducted in parallel with the engineering design of Target #3 to optimize the physics performance. The FLUKA Monte Carlo simulations for the different target designs proposed in this work were performed by the SY-STI-BMI section at CERN. The next sections summarize these optimization studies and their results.

Table 3.1. Key features of the n_TOF facility [37, 68].

Quantity	EAR1	EAR2
Neutron flux (n/bunch)	10^6	10^8
Energy range	min. subthermal max. 1 GeV	subthermal 100 MeV
Best resolution ($\Delta E/E$)	10^{-4}	10^{-3}

3.3.1 Neutron fluence

The key feature for both experimental areas is the high instantaneous neutron fluence [37, 68, 69], of fundamental importance for measuring cross-sections of radioactive samples or samples available in small quantities. The integrated flux of 10^6 and 10^8 neutrons/bunch in EAR1 and EAR2, respectively, is given by the high intensity and high energy of the primary proton beam and the overall mass of the target (especially the lead mass).

As shown in Fig. 3.6, Target #3 produces values of the neutron flux similar to or better than Target #2.

The shape of the neutron beam and, to some extent, its intensity, also depend on the moderator systems. When compared to Target #2, Target #3 has a slightly thinner layer of moderator liquid (water or borated water) crossed by neutrons directed towards EAR1. This results in an additional contribution of non-moderated neutrons at the evaporation peak (hundreds keV to several MeV) and, consequently, in a slightly lower neutron flux in the thermal and epithermal regions (≤ 100 eV). Overall, the neutron flux reaching EAR1 with Target #3 is 10% lower than with Target #2. Regarding EAR2, Target #3 leaves the neutron flux in the range 25 meV–100 keV essentially unchanged, while a factor 2-3 higher is expected at the evaporation peak. The higher flux is only indirectly related to the new target design, as it depends mainly on the new design of the vacuum window coupling the target to the beamline.

Moreover, the smaller amount of aluminum present in the structure of the Target #3 ensures a substantial reduction of the related absorption dips in the flux with respect to Target #2, as indicated by the black arrows in Fig. 3.6.

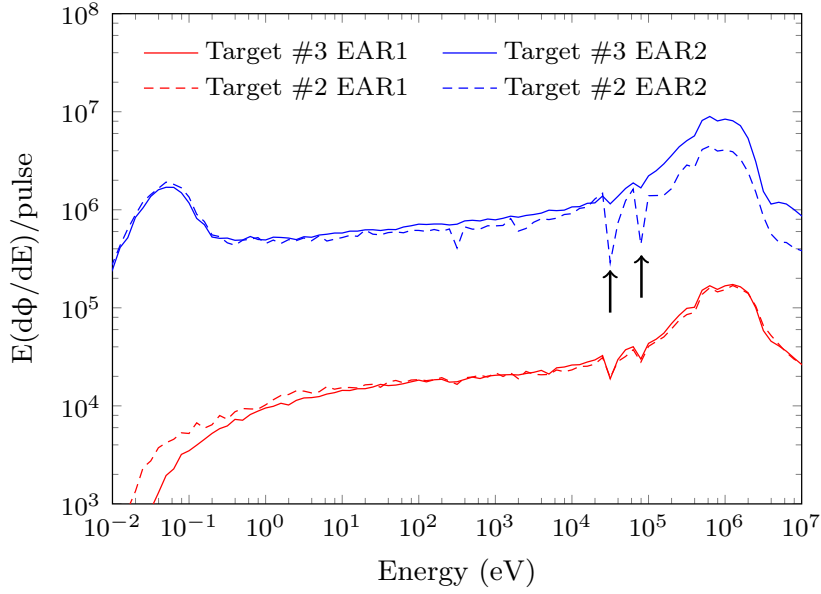


Figure 3.6. FLUKA simulation of the neutron flux in the two experimental areas for Target #2 and Target #3. The neutron flux in the energy range of interest is similar in EAR1 and much better for Target #3 in EAR2, especially considering the absence of absorption dips in the tens of keV range.

3.3.2 Resolution function

The neutron-induced reaction cross-sections under investigation at n_TOF exhibit narrow resonances in the eV–keV region. The energy resolution of the facility is of utmost importance to accurately determine the cross-sections in this energy range. Energy resolution essentially depends on the flight path of the two beamlines and on the neutron moderation. The resolution function can be expressed as the uncertainty $d\lambda$ in the equivalent flight path distance, and it is mainly dictated by the geometry of the moderator. In the energy range of interest it is characterized by a peak having a full width at half maximum (FWHM) of 2 cm caused by the pronounced slowdown in water, and a relatively small but long tail (up to several meters) caused by the moderation in the lead core.

FLUKA simulations showed that the optimum, in terms of FWHM, can be reached with water layers of 4 cm for both EAR1 and EAR2 moderators. While the new design does not show any difference in the EAR1 resolution function when compared to Target #2 [69], it significantly improves the scenario for EAR2. In the Target #3 design, particular attention was paid in making the neutrons traveling towards EAR2 pass through a uniform layer of moderator water. This was not the case for Target #2, built before the construction of the second beamline and therefore not optimized for it. Figure 3.7 shows the comparison of the λ distribution of neutrons in EAR2 in the energy range 1–10 eV for the two targets, revealing a double-peak structure for Target #2 that led to substantial limitations on the measurements in EAR2. The double-peak structure is not present in the λ distribution of Target #3, characterized by a much better FWHM around the peak.

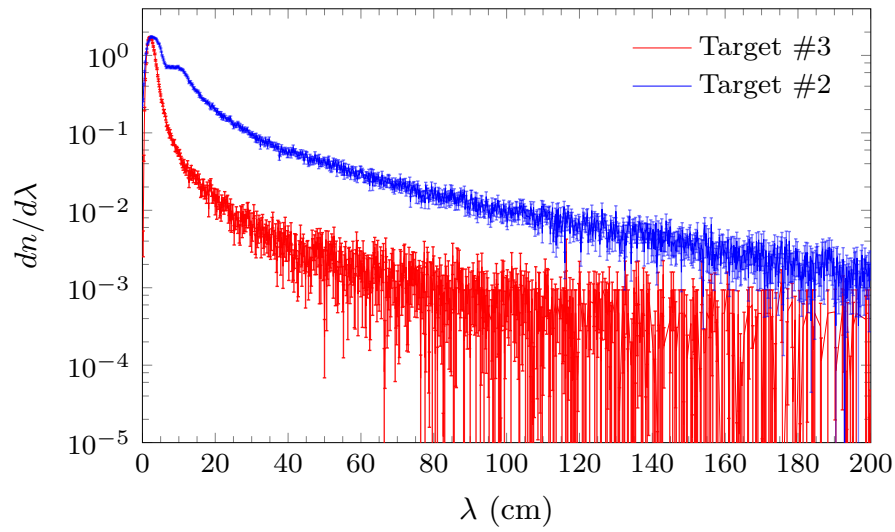


Figure 3.7. Distribution of the moderation length λ , in EAR2, for neutrons in the energy range 1–10 eV. Target #2 exhibits a double-peak structure leading to substantial limitations on the measurements in EAR2, whereas Target #3 exhibits a single peak with narrower FWHM, which is better suited for high-resolution neutron cross-section measurements.

3.3.3 Background

A low background is a fundamental prerequisite to carry out high-quality cross-section measurements. At n_TOF, the two main components of background related to the spallation target are uncorrelated neutrons and γ -rays.

The neutron contribution is proportional to the neutron flux and also depends on the optical elements placed in the neutron beamlines (i.e., collimators), so it is essentially unchanged in the new design. The contribution of γ -rays is strongly dependent on the target assembly and the materials it is made of. The γ -rays reaching the experimental areas can be divided into two contributions: *prompt* and *delayed*. The threshold between the two has been set at 900 ns for EAR1 and 200 ns for EAR2.

The prompt γ -rays reach EAR1 within 900 ns and EAR2 within 200 ns. Their amount is directly proportional to the length of lead crossed by the primary proton beam, so no sizable differences are expected in the new target design with regard to EAR1. For EAR2, on the other hand, the coupling between target and beamline has been improved with a new optimized shape of the vacuum chamber, so a larger portion of the spallation target is seen from the experimental area and the γ -ray contribution to the background increases by a factor of 6. To compensate for the higher background, a 5-cm thick lead plate has been integrated just above the target core and below the EAR2 moderator (Fig. 3.1). FLUKA simulations indicate that the addition of this lead plate is enough to keep the prompt γ -ray contribution to the background in EAR2 as low as for Target #2, with no significant reduction in the neutron flux reaching the area.

The delayed γ -rays reach EAR1 and EAR2 at a time-of-flight longer than 900 ns and 200 ns, respectively. They are generated from radiative capture reactions of neutrons in the hydrogen of the moderator water and in the materials of the target. The former can be inhibited using borated water, thanks to the very high relative thermal neutron capture in ^{10}B : for this reason, Target #3 includes two decoupled moderator circuits, with the possibility of changing independently the circulating moderator liquid. In addition, considerable effort was put into minimizing the structural materials of the target that are sources of delayed γ -rays. Figure 3.8 shows the FLUKA results of the delayed γ -ray background expected in EAR1 in comparison to Target #2, revealing a background lower by a factor 4-5, in particular at the 2.2-MeV energy peak and at the 7-MeV transition lines.

Regarding EAR2, γ -ray background arises mainly from the interaction of neutrons with the collimator at the entrance of the experimental area and with the beam dump in the roof of the building (Fig. 1.7) [70]. Therefore, the design of the target does not impact the delayed γ -ray background in EAR2.

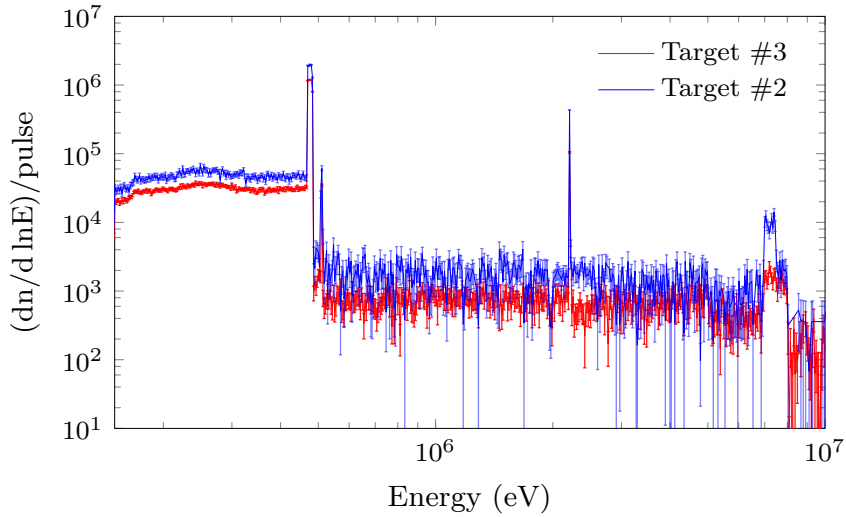


Figure 3.8. Delayed γ -ray distribution in EAR1 for Target #2 (blue) and Target #3 (red). A reduction by a factor 4-5 is visible in Target #3 at the 2.2-MeV energy peak and at the 7-MeV transition lines.

3.4 Nitrogen cooling system: Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) studies were carried out to support and optimize the design of the target. The optimization consisted in maximizing the cooling efficiency (minimizing the maximum steady-state temperature) while minimizing the pressure drop and the locations of high flow velocity inside the target. The CFD calculations also provided input for the thermo-mechanical analyses (see Sec. 3.5) and for the design of the cooling station (see Sec. 3.6).

The commercial CFD software ANSYS CFX [49] has been used throughout the studies to model

simultaneously the solid (lead slices) and the fluid bodies (nitrogen), and perform conjugate heat transfer calculations. The map of average beam power deposition, calculated with FLUKA Monte Carlo simulations, was imported as a power-generation boundary condition. The Shear Stress Transport (SST) turbulence model [71] was employed to accurately compute the momentum and the thermal boundary layers.

3.4.1 Design and performance optimization

Three components were mainly considered for the CFD design optimization: inlet and outlet ducts of the target vessel, cradle, and anti-creep plates.

The optimization was initially focused on tuning the number of inlets and outlets, their position, and size. The final configuration presents the best compromise between the target pressure drop and a balanced distribution of nitrogen flow, while complying with the space constraints of the assembly.

The cradle was designed to evenly distribute the nitrogen flow from the inlets to the channels between the lead slices. Large plenum volumes, as shown in Fig. 3.9, induce a deceleration of the fast flowing nitrogen, while their curved geometry inhibits flow separation at the walls due to the adverse pressure gradient, typical of a sudden expansion. As shown in Fig. 3.9, the incident beam axis forms a 10° angle with the target to reduce the EAR1 background caused by γ -rays and high-energy charged particles [40]. The beam is sufficiently diverging so that a dedicated dump is not required downstream the target in addition to the iron and marble already present around the target area. The cradle design is complemented with flow deflectors aligned with the beam axis to focus the cooling flow on the hottest regions of the lead surface.

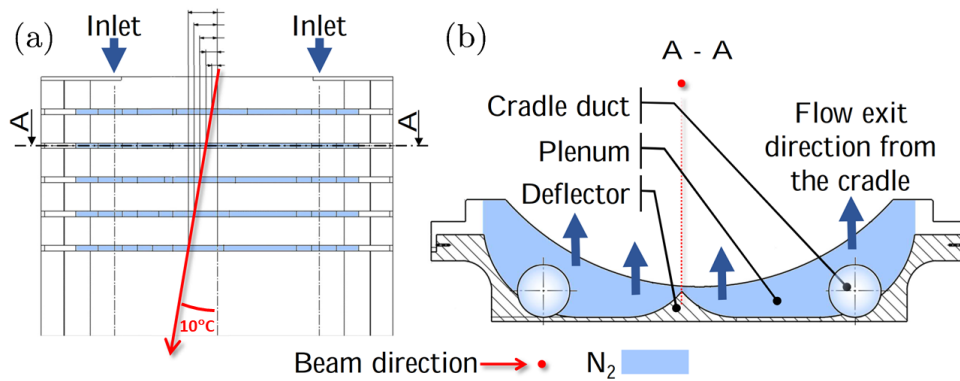


Figure 3.9. (a) Top view of the main core assembly (see also Fig. 3.1). Nitrogen flows through the channels machined in the anti-creep plates. The beam does not impact the lead surface perpendicularly, but at a 10° angle. (b) Cross-cut of the aluminum cradle through the second row of channels, showing the plenum volume and the geometry used to guide the flow into the channels.

The anti-creep plates drive the nitrogen flow over the lead surface while containing the creep deformation of the material. The flow-rate distribution among the channels is optimized by

adding partial wedge-shaped obstructions in the channels located farther from the beam, as schematically shown in Fig. 3.10 and Fig. 3.11. The geometry of these obstructing wedges was carefully designed to minimize pressure losses and flow disturbances.



Figure 3.10. Schematic view of the core assembly (see also Fig. 3.1) showing, highlighted in yellow, the channels with wedge-shaped obstructions. The obstructions partially restrict the flow in the channels located farther from the beam axis, increasing the flow rate on the regions of lead surface directly impacted by the beam.

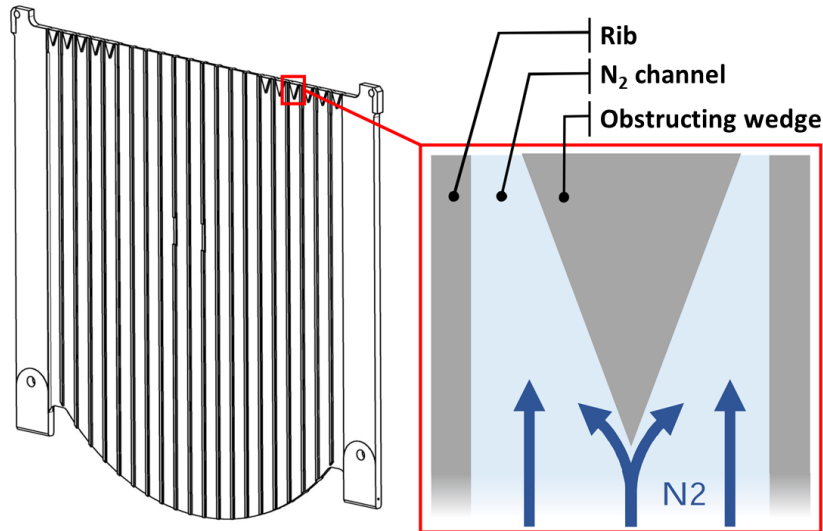


Figure 3.11. Example of an anti-creep plate and detail of the wedge-shaped obstructions. The obstructing wedges increase the pressure drop but help deliver higher flow rate on the regions of lead surface directly impacted by the beam.

3.4.2 Cooling performance

The cooling performance is presented for four operational cases, summarized in Table 3.2. Cases A and B reflect the two normal operational limits of the cooling station, while cases C and D assess the cooling performance when some of the cooling channels are obstructed by lead because of creep deformation (further details in Sec. 3.5). The cases C and D are defined by considering no flow nor heat transfer in the channels that are adjacent to the lead surfaces where the highest temperature values (and creep deformations) are expected. The channels simulated as obstructed are the ones closest to the beamline, on both faces of the 2nd slice and on the downstream face of the 6th slice (according to the nomenclature in Fig. 3.10). For each of these faces, three channels are considered obstructed in scenario C, while five channels are considered obstructed in scenario D. Given the expected creep deformations discussed in Sec. 3.5, these two scenarios represent rather conservative degraded configurations.

Table 3.2. Normal and degraded scenarios simulated for cooling performance assessment.

Case	n° clogged channels	Volume flow (Nm ³ /h)
A	0	800
B	0	1000
C	3	800
D	5	800

Considering a beam average power of 5.4 kW (2.7 kW absorbed by the lead slices) and a beam size of 15 mm (1σ), the maximum steady-state temperature in each slice is reported in Fig. 3.12, and it appears correlated with the heat absorbed by each slice. The 1st and 6th slices are exceptions: the 1st slice absorbs the lowest amount of heat without being the coldest one, while the 6th slice absorbs the highest amount of heat without being the hottest one. This is caused by the fact that the 1st slice is cooled only on one side, while the 6th slice is subjected to an energy deposition more evenly distributed and a lower peak compared to the 2nd slice.

The maximum steady-state temperature values occur in the 2nd and 6th slices, ranging between 85–89°C and 83–90°C, respectively, and depending on the nitrogen flow. These values increase in the degraded configurations, with the 2nd slice experiencing the highest increase (25% for case D). Within each slice, the temperature is highest close to the beam axis, as shown in Fig. 3.13.

For the downstream and upstream face of the 2nd and 6th slices, respectively, the temperature profile along the horizontal at the height of the beam axis is shown in Fig. 3.14. The average velocity of the nitrogen flow in the corresponding channels is also represented: the speed is higher in the channels without obstructing wedges, which leads to a higher heat transfer coefficient (HTC) on the regions where most of the beam power is absorbed.

The pressure drop estimated by simulations and the peak value of velocity in the target for the

two operational cases are listed in Table 3.3. The blockage of cooling channels due to creep, as in case D, results in an increase of 6% in pressure drop, which is well within the range in which the cooling station can operate.

The analysis also shows that the nitrogen velocities in the target are below Mach 0.3, thus

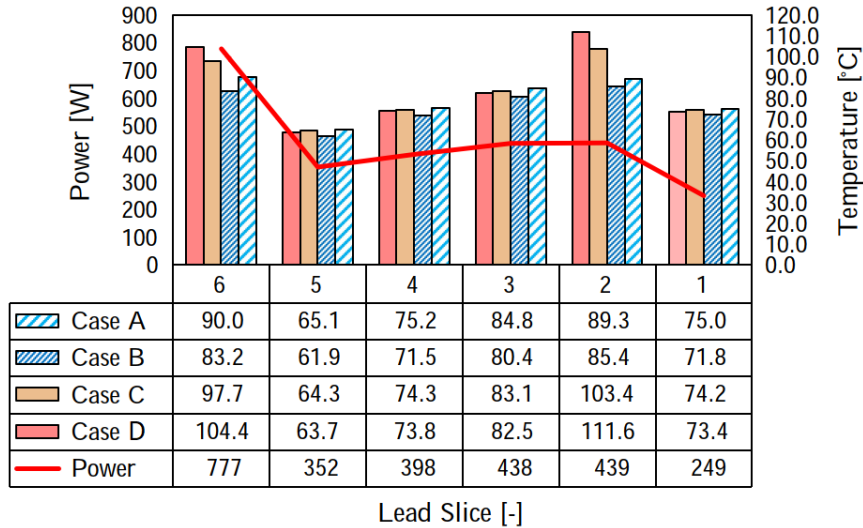


Figure 3.12. Maximum steady-state temperature in each lead slice and scenario described in Table 3.2, considering an average beam power of 5.4 kW and a beam size of 15 mm (1σ). The highest temperature is reached in the 2nd slice, followed by the 6th slice.

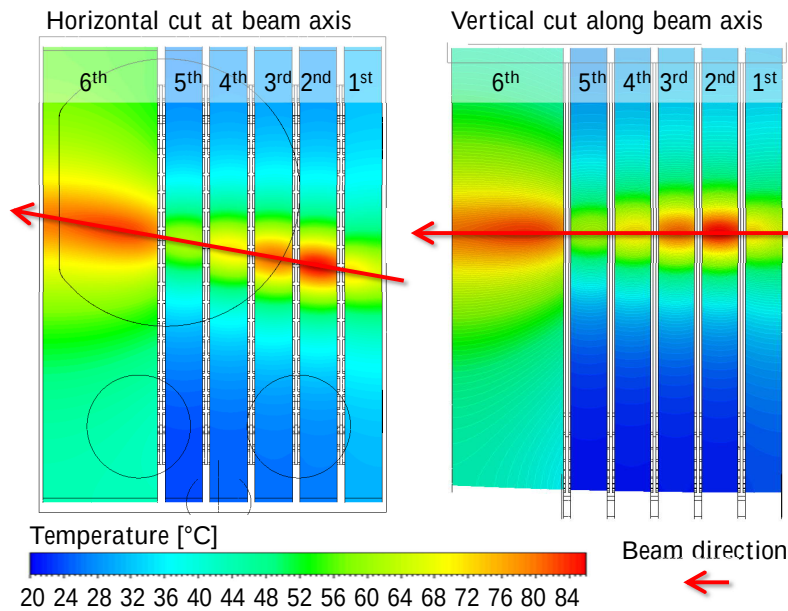


Figure 3.13. Steady-state temperature distribution in the lead slices, cross-sections intersecting the beam axis. The beam axis is not orthogonal to the lead surface, but tilted by 10° in the horizontal plane to reduce the EAR1 background caused by γ -rays and high-energy charged particles, as explained in Sec. 1.2.3.

3.4. Nitrogen cooling system: Computational Fluid Dynamics

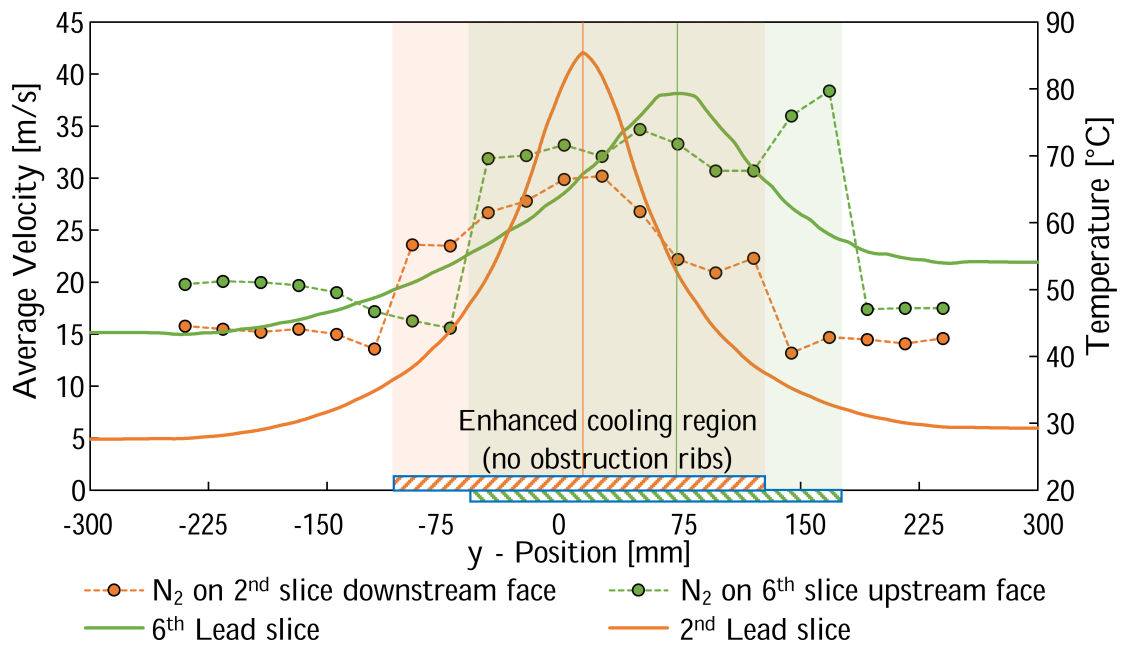


Figure 3.14. Steady-state temperature profile along the horizontal at the height of the beam axis, for the downstream and upstream face of the 2nd and 6th slices, and average nitrogen velocity in the corresponding cooling channels.

Table 3.3. Nitrogen pressure drop in the target and peak velocity values for the four scenarios described in Table 3.2.

	A	B	C	D
Pressure drop (kPa)	4.7	7.0	4.8	5.0
Maximum velocity (m/s)	77.2	89.5		

the flow can be considered incompressible everywhere, with the highest velocities occurring at the bend of the vessel inlets. Inside the target vessel, specifically in the cradle ducts, the nitrogen flows relatively fast, decelerating as it flows into the plenums along the ducts. The analysis results reveal that velocities up to 65 m/s are expected to occur at the entrance of a few channels because of the apparent cross section reduction and flow separation at the entrance of the channels. The nitrogen flowing through the narrow sections beside the obstruction wedges can reach velocities between 70 m/s and 87 m/s for cases A and B, respectively; however, the velocities at the beam impinging spots are below 40 m/s. The highest velocity values, besides taking place in limited and localized areas over colder lead surfaces, are within the acceptable threshold value of 110 m/s to avoid erosion (according to [72]).

3.5 Thermo-mechanical assessment of the lead core

The time evolution of temperature, stress, and strain in the target were estimated by means of CFD and FEM analyses with ANSYS and LS-DYNA [49].

3.5.1 Thermal analyses

The temperature dependence of every material property has been included in the analyses. The reference sources for the thermal properties are [73–75].

For a 36-s supercycle with an average beam intensity of $1.67 \times 10^{12} \text{ p}^+/\text{s}$, the most conservative approach in terms of beam load is considering six pulses hitting the target consecutively with the minimum repetition rate of 1.2 s. The six pulses are then followed by a cool-down of 30 s. The load boundary condition for the thermal analyses is a power generation field in the target, resulting from the interaction between beam and target and obtained by means of FLUKA Monte Carlo simulations.

The cooling effect of nitrogen is modeled by a convective boundary condition where the heat transfer coefficient (HTC) field was imported from the CFD simulations described in Sec. 3.4. The average HTC is $63.8 \text{ W m}^{-2} \text{ K}^{-1}$, but the flow is optimized to be faster at the beam impinging spot, where the HTC reaches a value of $130 \text{ W m}^{-2} \text{ K}^{-1}$.

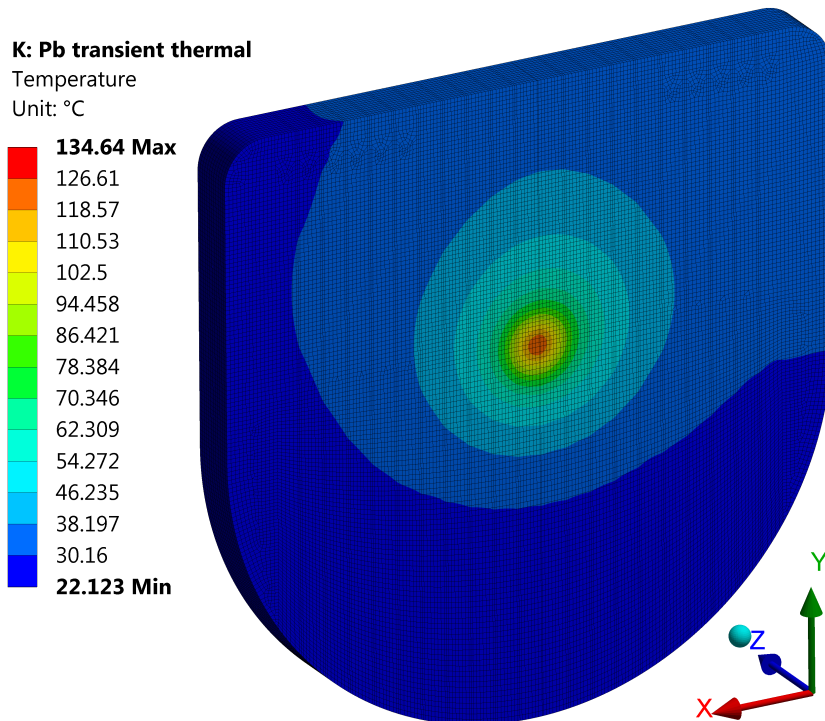


Figure 3.15. Temperature map, in the 2nd lead slice crossed by the beam, at the instant of peak temperature. The peak temperature is equal to 135°C .

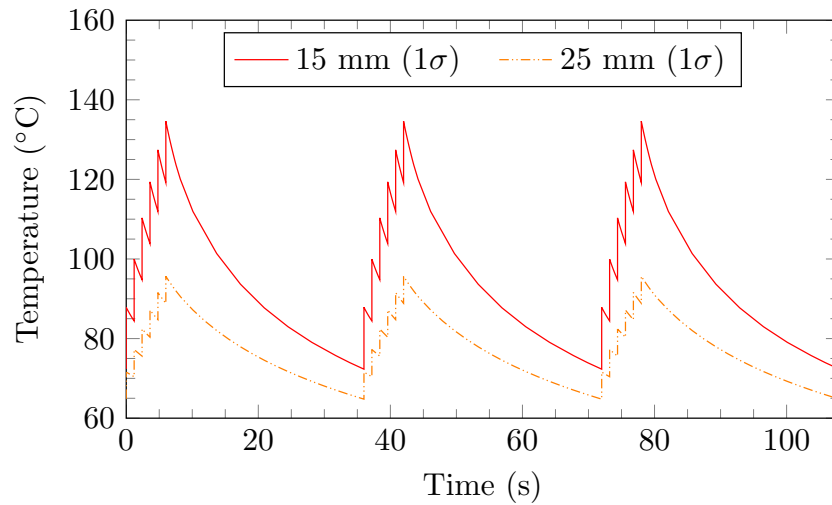


Figure 3.16. Maximum temperature in the target Pb core during three 36-s supercycles once periodic steady state is reached, with beam size of 15 mm and 25 mm (1σ).

The 2nd lead slice crossed by the beam is subject to the highest energy deposition and temperature. The results of thermal simulations for this slice are shown in Fig. 3.15 and 3.16: Fig. 3.15 shows the temperature field at the instant of peak temperature, while Fig. 3.16 shows the plot of maximum temperature vs. time during three 36-s supercycles, once periodic steady state is reached. The peak temperature is 135°C, safely lower than the melting point of lead (327°C) but high enough to significantly decrease strength and promote creep. Figure 3.16 also shows the benefits of a change of optics, if feasible: a larger beam size (25 mm 1σ) reduces the peak temperature to 96°C.

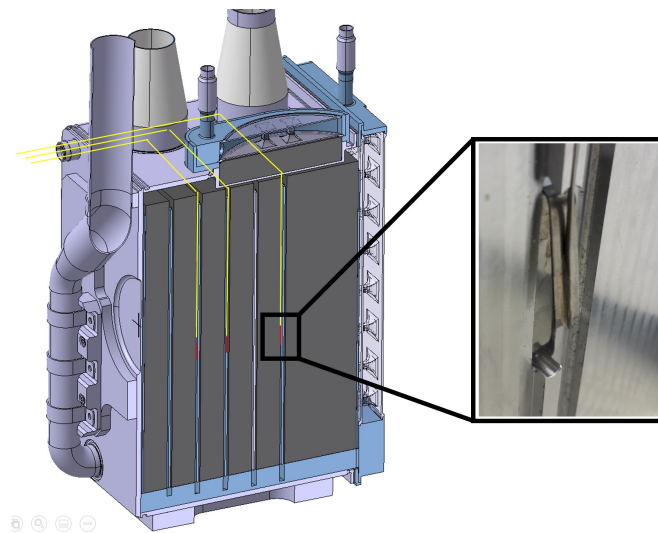


Figure 3.17. Thermocouples mounted in the Target #3 core to measure temperature on the surface of the lead slices. The thermocouples are pushed against the lead surface by elastic elements mounted in the aluminum EN AW-6082 plates.

A series of six radiation-hard thermocouples have been placed inside the target, directly in contact with the lead slices [41]. The thermocouples are placed close to the beam axis, pushed by elastic elements mounted in the aluminum EN AW-6082 plates against the surface of the lead slices (Fig. 3.17).

Although the thermocouples can provide benchmarks for the thermal simulations and feedback on the status of the target core, they are not essential for the target operation in case they fail prematurely.

3.5.2 Stress analyses

Mechanical stresses arise in the target for two main reasons: quasi-static loads and dynamic loads. Quasi-static loads are induced by heat from the average beam power absorbed in the target, which provokes temperature and thermal expansion gradients inducing mechanical stress. Dynamic loads are induced by the impulsive nature of each beam pulse, which is absorbed in 7 ns (1σ). This provokes an impulsive temperature rise and consequent thermal expansion, which causes the propagation of stress waves and induces dynamic stresses as described in Sec. 2.1.2.

The properties used for the structural analyses are taken from [61, 62, 76]. Two constitutive models were used to model plasticity: pure isotropic hardening (without Bauschinger effect), and pure kinematic hardening (with Bauschinger effect) [77]. Material characterization activities were carried out to develop a nonlinear kinematic hardening model for plasticity of pure lead. More details on these activities are reported in Chap. 5.

Figures 3.18 and 3.19 show some of the results of the structural simulations. Figure 3.18 shows the von Mises equivalent stress map during the stress-wave propagation stage. Figure 3.19 shows the oscillations, due to dynamic effects, of the von Mises equivalent stress after the sixth (and last) pulse in a supercycle. The peak value of von Mises stress is 2.6 MPa, while pressure and maximum principal stress reach 80 MPa: the hydrostatic component of stress is dominant. The stress level is quite high if compared to the strength of pure lead (plastic flow begins below 1 MPa [62]) and to the fatigue strength values shown in Table 2.15.

However, it is important to consider, as anticipated in Sec. 2.3.7, that the fatigue strength of lead in absence of oxygen, at room temperature and 4×10^7 cycles, is 2.3 times the one in air [62, 67], although the magnitude of the improvement is not known at higher temperatures. In addition, it is worth recalling here the high number of cycles to which the pure lead core is subjected (on the order of 10^8 cycles), the complex loading conditions (multiaxial cyclic plasticity with varying temperatures), and the presence of complex effects in the constitutive behavior of pure lead (a more detailed description is offered in Chap. 5). Under these conditions, the numerical models used to predict the actual damage in the pure lead core at the end of the entire target lifetime are characterized by high uncertainty, which is best supported by physical testing.

Thus, a target prototype was tested under beam irradiation in the HiRadMat facility at

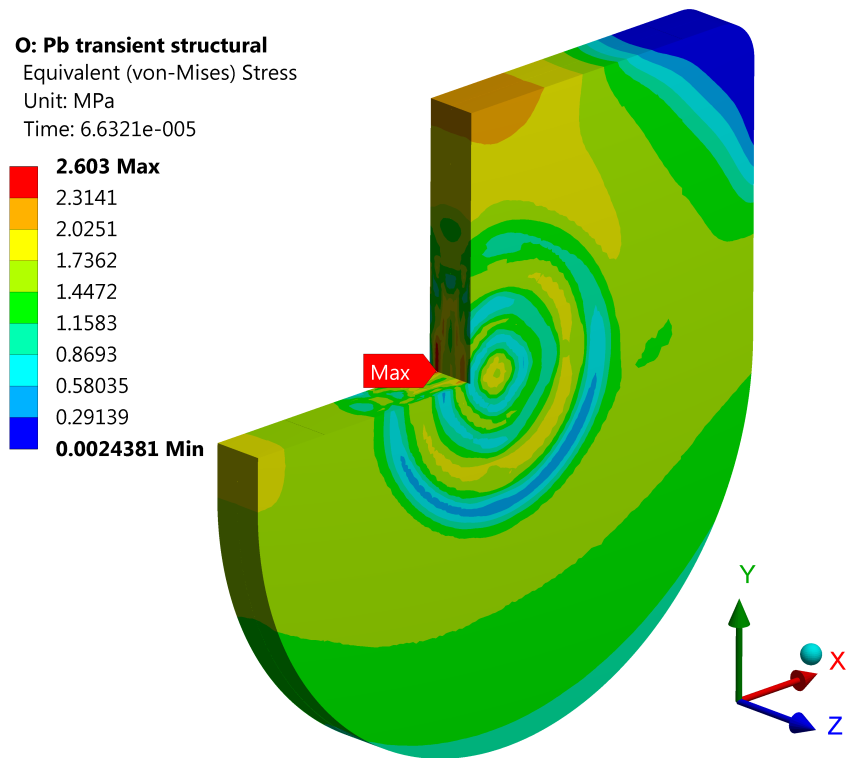


Figure 3.18. Peak von Mises equivalent stress in the target lead core during propagation of stress waves. The stress waves start propagating radially from the area of impact on the proton beam axis.

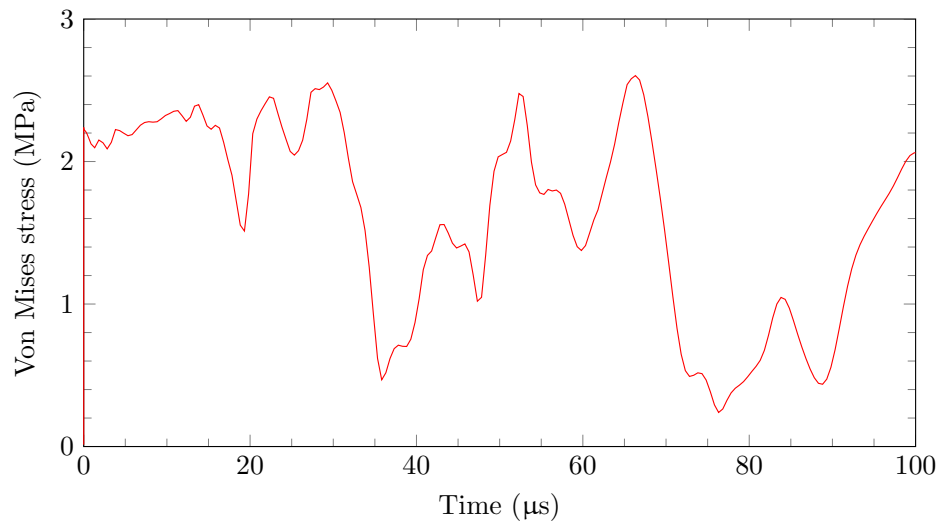


Figure 3.19. Von Mises stress vs. time in the target Pb core after the sixth (and last) pulse of a supercycle. The oscillations are provoked by the instantaneous temperature spike due to heat dissipation of the beam pulse.

CERN [78]. The outcome of the beam irradiation test was positive as no defects and internal voids were observed inside the material by neutron tomography inspections [40]. Further

details of this beam irradiation test will be presented in Chap. 4.

In addition, a model capable of reproducing complex effects in the constitutive behavior of pure lead is proposed in Chap. 5, initiating a process to improve numerical models aimed at predicting the long-term material evolution. Recommendations for future developments of this process are proposed in the conclusions.

3.5.3 Creep analyses

Pure lead is strongly affected by creep, i.e. plastic flow of material with time under constant stress, especially at the temperature reached in the n_TOF target (135°C max.). Creep phenomena could induce lead to flow into some of the cooling channels, obstructing them and reducing the cooling efficiency. The creep strain rate for each level of temperature and stress is plotted in the *deformation-mechanism maps* [76]. The data for pure lead was digitized to obtain the curves in Fig. 3.20.

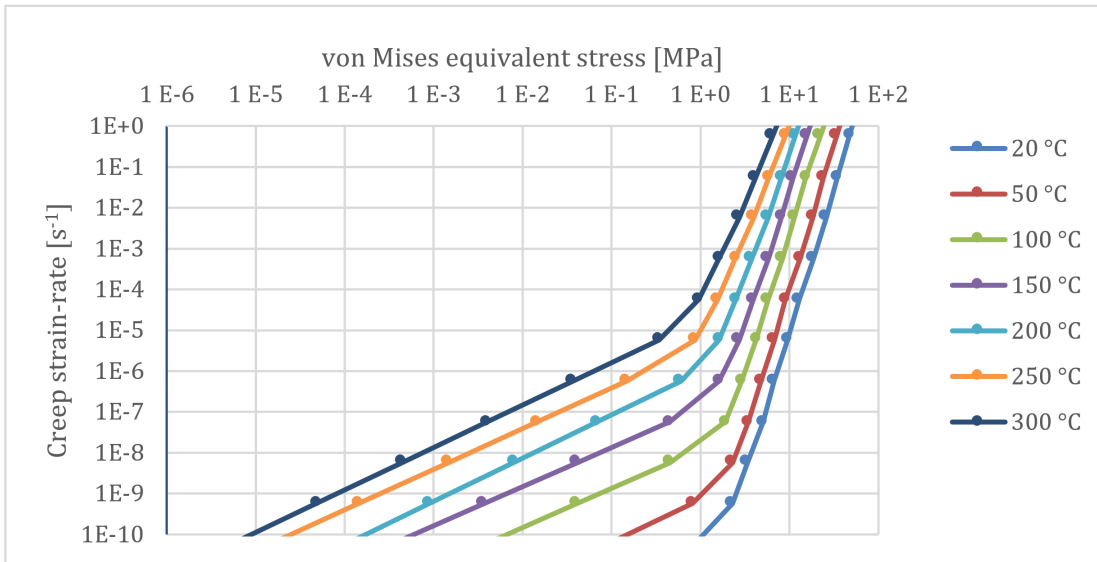


Figure 3.20. Creep strain-rate in pure lead for different values of temperature and von Mises stress.

For each temperature on a log-log plane, the curves in Fig. 3.20 seem to follow straight lines with a mild slope (diffusional flow) up to a transition in the 1-2 MPa range; at higher stress, the curves follow straight lines with a steeper slope (power-law creep mechanism). A constitutive model able to reproduce lead creep over all the stress and temperature ranges of interest for the n_TOF target is not readily available in ANSYS; thus, a new model was coded as User Programmable Feature (UPF). The new model consists of a series of piecewise functions, each composed of multiple power laws of the kind:

$$\dot{\epsilon} = c \sigma^n$$

where $\dot{\epsilon}$ is the creep strain-rate, σ is the von Mises equivalent stress, c and n are coefficients. The value of n (slope of the straight lines in a log-log plane) is about 1 for diffusional flow mechanism and between 5 and 7 for power-law creep. Each piecewise function reproduces the deformation-mechanism maps for a single temperature; the creep strain rates for intermediate temperatures are obtained by logarithmic interpolation.

The sixth (and last) lead slice intersected by the beam is the thickest (15 cm) and is subjected to the largest creep deformations. A simulation, featuring the new creep constitutive model, was performed to estimate the maximum penetration, due to creep, of the lead slice into the cooling channels. Figure 3.21 show the model used for the simulations: it includes the 15-cm

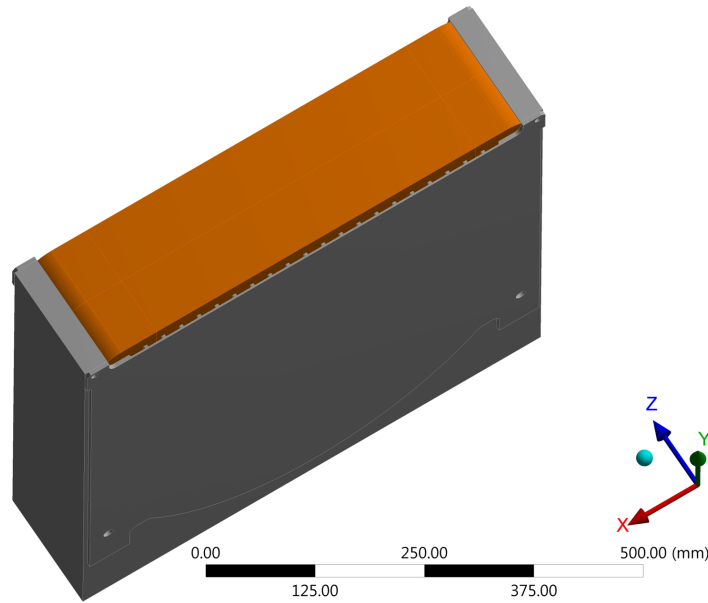


Figure 3.21. FEM model of the downstream lead slice for creep simulation.

lead slice, the two aluminum EN AW-6082 T6 anti-creep plates in contact with it, and the EN AW-6082 T6 cradle. For this simulation, the aluminum parts were modelled as perfect rigid bodies, and the initial gaps between the lead slice and the anti-creep plates were neglected. These assumptions are conservative if the objective is to estimate the maximum penetration of the lead slice in the cooling channels. The loads considered in the analysis are the weight of the slices and the temperature field at the instant of peak temperature. The temperature field is conservatively assumed to be constantly applied for 2×10^8 s (approximately 6 years and 4 months of continuous operation, twice the target lifetime). The resulting displacements are shown in Fig. 3.22: the maximum penetration is 0.64 mm, whereas the channel depth is 3 mm.

As described in Sec. 3.4, degraded scenarios including the possibility of obstructed channels were considered in CFD simulations. The results of this analysis shows that the target operation would not be compromised: the lead slice would be subject to a maximum peak temperature of 160°C , which is considered acceptable for the degraded scenario under examination.

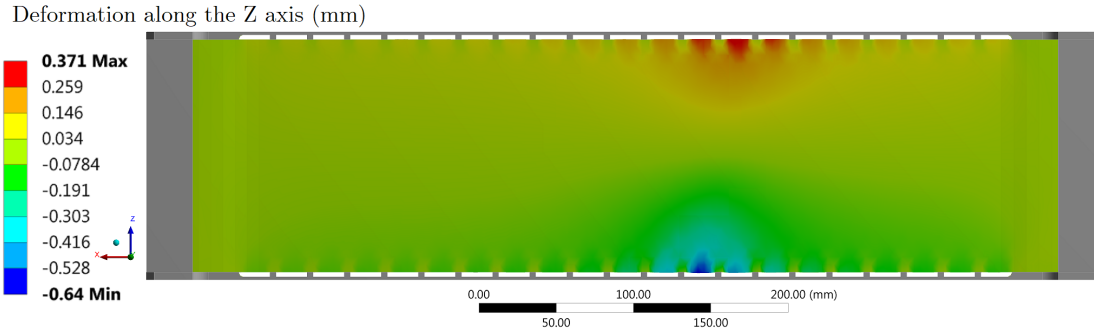


Figure 3.22. Penetration, due to creep, of the 15-cm thick lead slice into the cooling channels (view from the top, cross-section cut through the point of maximum penetration). The gray parts are the aluminum (EN AW-6082 T6) anti-creep plates with the cooling channels. The color map shows the maximum projected displacements after 2×10^8 s (approximately 6 years and 4 months of continuous operation, twice the target lifetime).

3.6 Design of the nitrogen cooling station

The nitrogen gas for the target cooling system is produced by a nitrogen generator, recirculated in the cooling circuit by an ad-hoc compressor, and cooled by chilled water. The design requirements of the nitrogen cooling system are summarized in Table 3.4. The nitrogen flow is filtered by High Efficiency Particulate Air (HEPA) and active carbon filters to capture particles and volatile compounds released by the spallation target in the nitrogen stream. The part of the cooling system between the target vessel and the filter casing containing the filters is enclosed in a sealed room under dynamic confinement: an extractor ensures that the pressure in the sealed room is lower than the surrounding environment in order to control potential radioactive releases. In case of a leak of activated nitrogen from the filter casing, the radioactive gas is therefore contained in the sealed room and extracted to a dedicated ventilation system in the target tunnel area. The maximum leak rate in the unconfined part of the circuit that has been considered acceptable after radiation protection studies is 5 L/h. Leak measurements performed during the commissioning of the cooling station showed a significantly lower leak rate, below 3×10^{-4} L/h.

Table 3.4. Nitrogen cooling station: cooling requirements.

Quantity	Value
Cooling power	2.6 kW
Nominal flow rate	780 Nm ³ /h
Pressure drop	30 mbar
Gas supply temperature	20 ± 2 °C
Maximum pressure	500 mbar

The cooling station supplies nitrogen gas to cool the target lead slices via AISI 304L stainless steel pipes. The main elements of the cooling station are shown in Fig. 3.23.

3.6. Design of the nitrogen cooling station

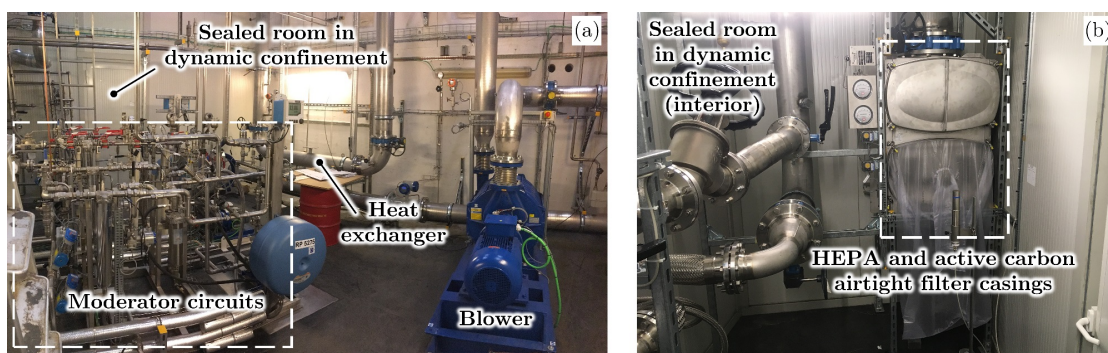


Figure 3.23. (a) Main components of the cooling and moderator station. The cooling nitrogen is compressed in the blower, cooled down in the heat exchanger, and filtered upstream and downstream the target. The station also includes the two separate moderator circuits for EAR1 and EAR2, which can work independently with demineralized water or borated water. The filters are located inside an airtight room in dynamic confinement. (b) Photo inside the airtight room in dynamic confinement. The HEPA and active-carbon filter capture particles and volatile compounds in the nitrogen stream.

The gas compressor (blower) is a multistage centrifugal compressor with a maximum flow rate of $1000 \text{ Nm}^3/\text{h}$ and a pressure rise of 285 mbar. It integrates features to minimize gas leaks such as magnetic coupling between compressor shaft and motor, silicone groove O-rings between casing discs, and EPDM (ethylene propylene diene monomer rubber) seals at all bolted flanges. The 29-kW heat exchanger is installed downstream of the blower to cool the hot nitrogen gas down to 20°C via chilled water. It is of tubular type to minimize the pressure drop and has tubes arranged in horizontal configuration. The nitrogen stream is filtered by a HEPA filter upstream of the target and by a double-stage nuclear-grade HEPA plus active-carbon filter downstream of the target. Class 3 (ISO 10648-2) gas-tight filter casings host all of the filters. The casing design allows the filter status to be monitored and the filters to be replaced without contact with nitrogen. The HEPA filters capture particles and aerosols with an efficiency greater than 99.98% for a minimum particle size of $0.15 \mu\text{m}$. The active carbon filter captures any volatile compound released in the nitrogen gas stream. A gas-analysis system based on quadrupole mass spectrometry analyzes continuously the gas composition upstream and downstream of the double-stage filter casing with the HEPA and the active carbon filters. As previously mentioned, the filters are installed inside a sealed room kept in dynamic confinement via an extraction fan.

4 Tests of target prototypes under beam irradiation

4.1 Introduction

Small-scale prototypes of the two most promising target design concepts were tested under proton beam irradiation in the CERN HiRadMat facility, in the SPS. Figure 4.1 shows that one prototype is representative of the core of the Ti-6Al-4V-clad lead concept, while the other is a small-scale prototype of the nitrogen-cooled bare-lead design (finally chosen as Target #3

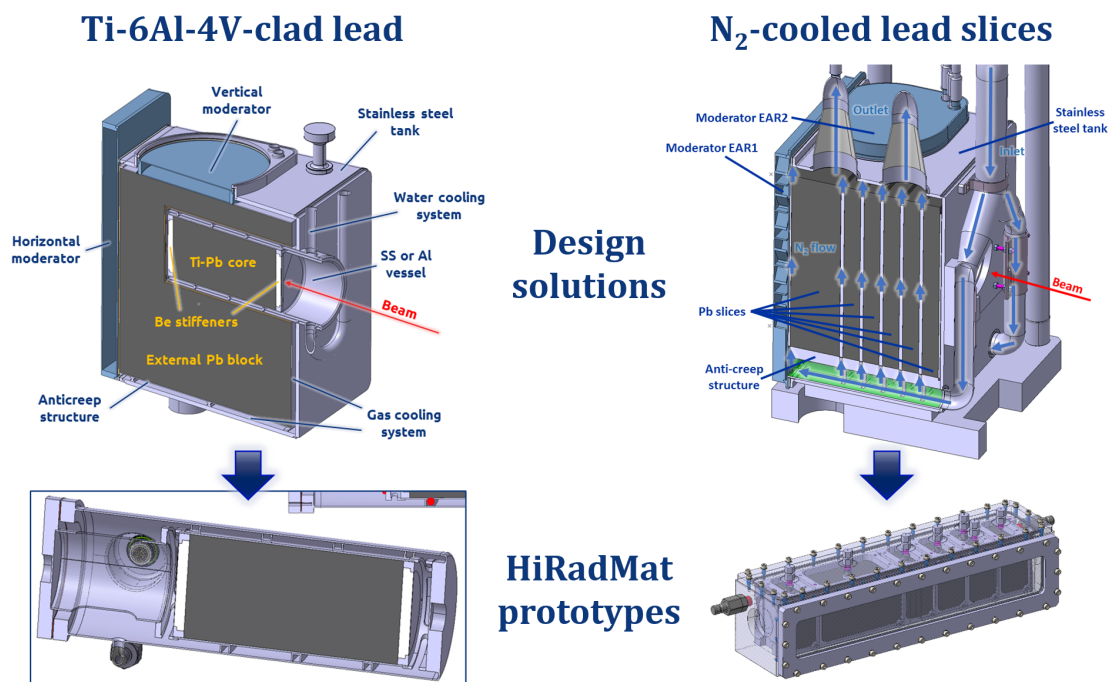


Figure 4.1. Small-scale prototypes of the two most promising target design concepts tested under proton beam irradiation in the CERN HiRadMat facility. Left: prototype of the Ti-6Al-4V-clad lead core with beryllium stiffening plates. Right: prototype of the nitrogen-cooled concept, finally adopted as Target #3 design.

design).

The HiRadMat (High-Radiation to Materials) facility at CERN allows users to perform beam irradiation tests with high-intensity proton beam pulses on material samples as well as accelerator components assemblies [78]. Up to 3.5×10^{13} protons with a momentum of 440 GeV/c can be delivered in short pulses of about 8 μ s. The proton beam is extracted from the Super Proton Synchrotron (SPS) accelerator ring at CERN.

4.1.1 Prototype of the nitrogen-cooled lead concept: description

The prototype of the adopted design solution of the n_TOF Target #3 (Fig. 4.2) consists of six pure lead blocks with a size of $80 \times 80 \times 50$ mm³, with the exception of one block with a size of $80 \times 80 \times 150$ mm³. The six blocks are supported by an EN AW-6082 T6 structure and are contained in a vessel made from the same aluminium alloy filled with nitrogen. On the beam impact areas, both on the upstream and downstream faces, the EN AW-6082 T6 vessel has a thickness reduced to 2 mm to minimize the interaction with the proton beam (beam window) that could damage the vessel. The vessel is filled with nitrogen through an inlet and outlet consisting of quick coupling mechanisms. The gas-tightness of the EN AW-6082 T6 vessel is ensured by EPDM O-rings. Seven thermocouples are installed on the lead blocks to monitor their temperature during the beam irradiation test and confirm that it was in the desired range. Each block was equipped with one thermocouple on the top surface (about 4 cm above the center of the beam impact spot) with the exception of the fifth block along the beam

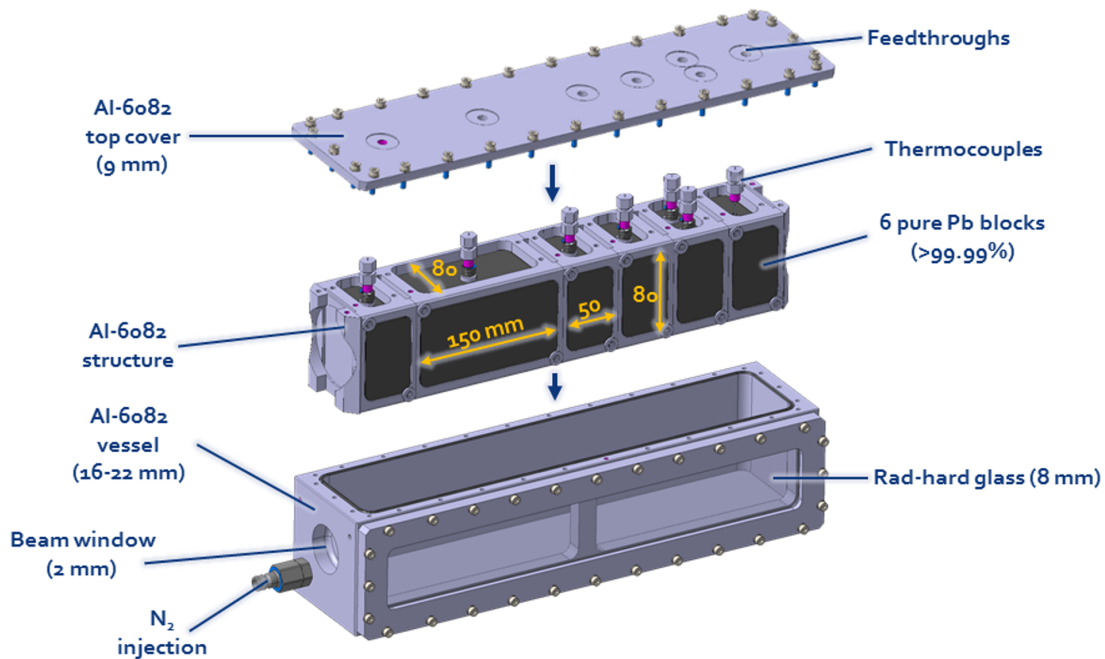


Figure 4.2. Small-scale prototype of the n_TOF Target #3 for the HiRadMat beam irradiation test (exploded view).

direction, which was equipped with two thermocouples. The difference between them was the presence of thermal paste. The purpose was to compare the temperature measurement with and without thermal paste, since in Target #3 thermal paste between lead slices and thermocouples cannot be applied because of potential degradation from long-term radiation. The connection between the thermocouples and the EN AW-6082 T6 vessel was made with graphite seal fittings. One side of the EN AW-6082 T6 vessel was equipped with a window and a radiation-hard glass. An online radiation-hard camera was pointed towards the window to give a live view of the irradiated lead blocks during the beam test.

4.1.2 Prototype of the Ti-6Al-4V-clad lead concept: description

The prototype of the Ti-6Al-4V-clad lead concept consists of a lead cylinder ($\varnothing 150 \text{ mm} \times 300 \text{ mm}$) contained in a 1.5-mm thick Ti-6Al-4V container. The lids of the Ti-6Al-4V container are 0.5-mm thick and are stiffened by two 15-mm thick beryllium plates (Fig. 4.3). This core assembly is contained in a stainless-steel water vessel to provide active water cooling to the prototype using as supply the water line in the HiRadMat experimental area (Fig. 4.4). This beam irradiation test had the objective of assessing the ability of the Ti-6Al-4V container to withstand repeated high-intensity beam pulses.

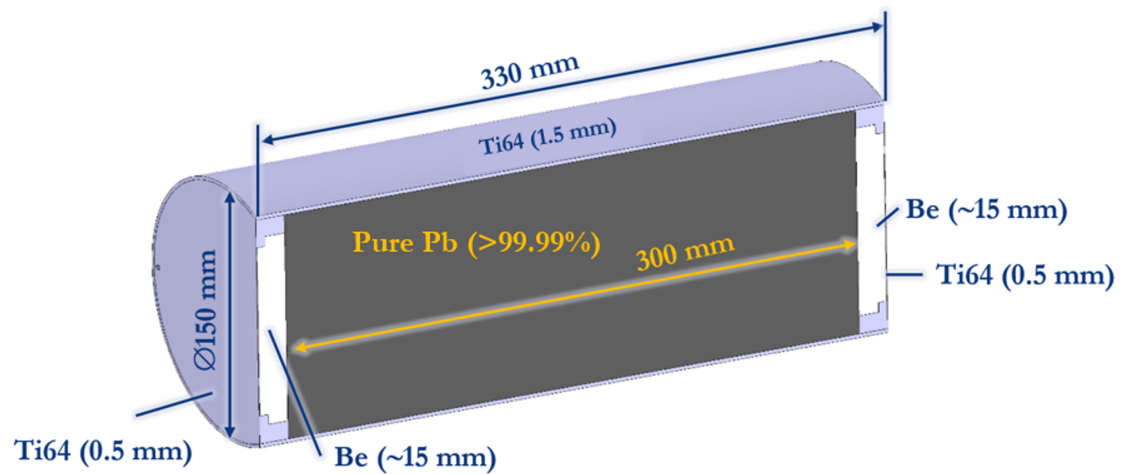


Figure 4.3. Prototype of the Ti-6Al-4V-clad lead concept for the HiRadMat beam irradiation test (3D CAD model section view).

4.2 Beam irradiation test setup

The two prototypes, when installed in the irradiation area, must be contained in a tank made of aluminium alloy because of radioprotection, handling, and safety rules. The tank is shown in Fig. 4.5. It was shared among the two prototypes described and the samples of two other beam tests. Figure 4.5 shows that the aluminium tank is composed of two modules: the upstream module (along the beam direction) was supporting samples for other beam tests,

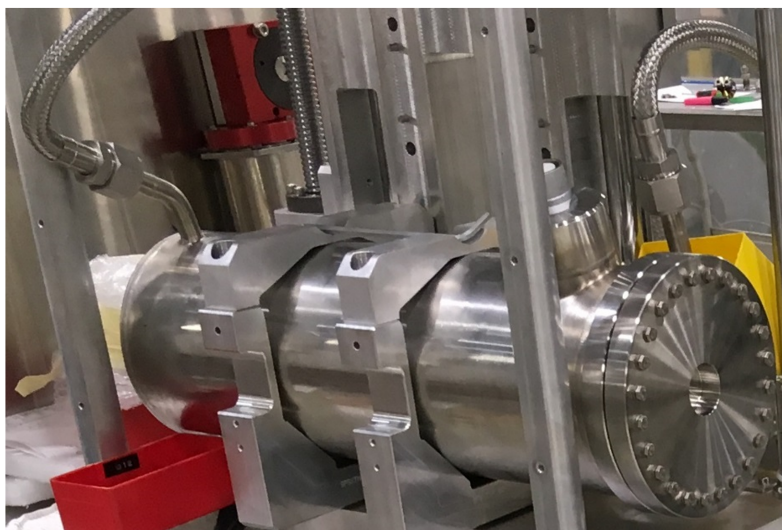


Figure 4.4. Prototype of the Ti-6Al-4V-clad lead concept for the HiRadMat beam irradiation test: photo of the external stainless-steel water vessel.

while the downstream module was supporting the two n_TOF prototypes. To align the center of each prototype to the beam for the irradiation test, the tank is equipped with a series of step motors. Each module is equipped with independent step motors move vertically and align the prototype of one module to the beam while the samples of the other module are in parking position (out of the beam path). Figure 4.6 shows a photo of the assembled test setup before being placed in the HiRadMat experimental area.

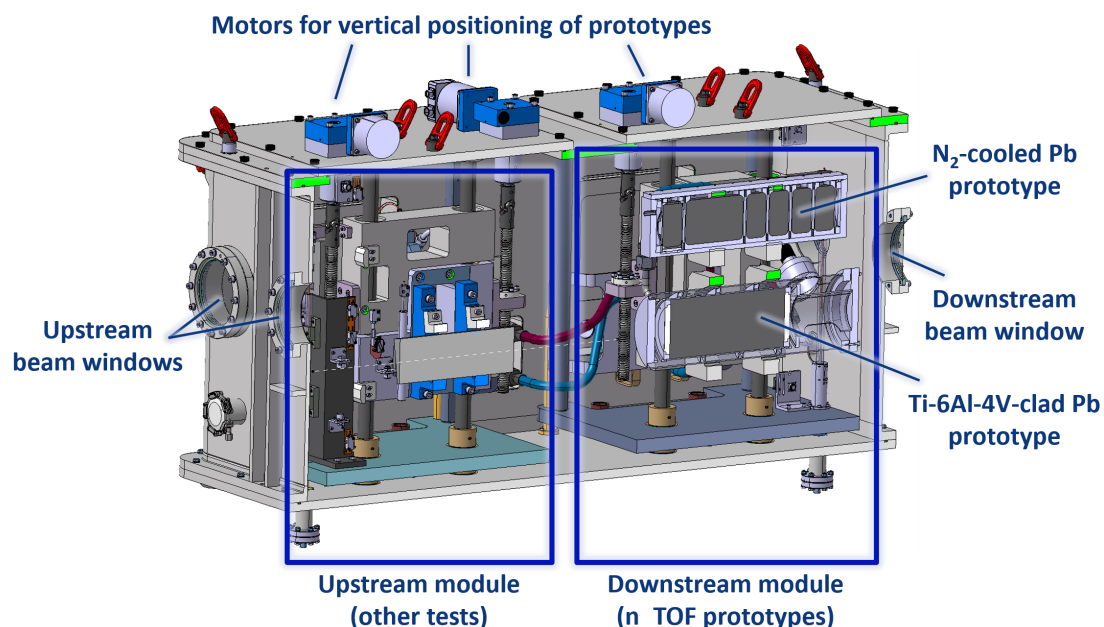


Figure 4.5. HiRadMat beam irradiation test setup. The two prototypes for the n_TOF test are located in the downstream module.

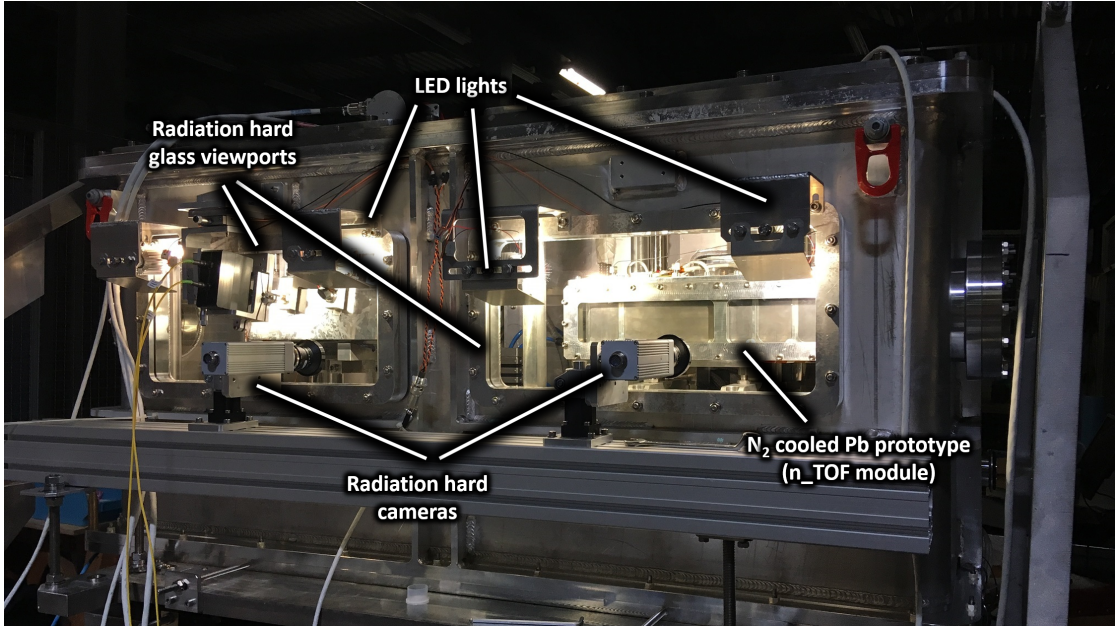


Figure 4.6. Assembled HiRadMat test setup. The radiation-hard glass windows and cameras offer a live view of the irradiated prototypes during the beam test.

4.3 Prototype of the nitrogen-cooled lead concept: beam irradiation test

The purpose of the beam irradiation test on the nitrogen-cooled lead prototype was to observe, by post-irradiation examinations (PIE), the conditions of the lead blocks after being irradiated by repeated beam impacts at temperatures ranging between 100 and 140°C (as in Target #3, Sec. 3.5.1).

The temperature in each block was kept steady at the desired values thanks to a series of heating foils and thermocouples attached to the EN AW-6082 T6 vessel. The power provided by the heating foils was automatically regulated, during the beam irradiation test, to keep the temperature of the EN AW-6082 T6 vessel as measured by the thermocouples within the desired range. Figure 4.7 shows two photos of the assembled prototype with thermocouples and heating foils. The minimum power to be provided by the heating foils to reach the desired temperature in the lead blocks was defined with the help of CFD simulations (Fig. 4.8). These simulations took into account the convective flow of the nitrogen gas in the vessel and the average beam power dissipated in the lead blocks to estimate the temperature in the lead blocks depending on the power provided by the heating foils (Fig. 4.8).

This prototype was impacted by 1500 proton-beam pulses with an intensity ranging between 4 and 4.5×10^{10} protons, a duration of 1.6 ns (4σ), and with a repetition period of 22.8 s. The PS beam impacting the n_TOF target has a momentum of 20 GeV/c, while the SPS beam delivered to the HiRadMat facility and the prototype had a momentum of 440 GeV/c. An



Figure 4.7. Left: picture of the assembled prototype of Target #3 tested under beam irradiation in the CERN HiRadMat facility. Right: heating foils attached to one side of the EN AW-6082 T6 vessel to keep the temperature in the desired range during the beam irradiation test.

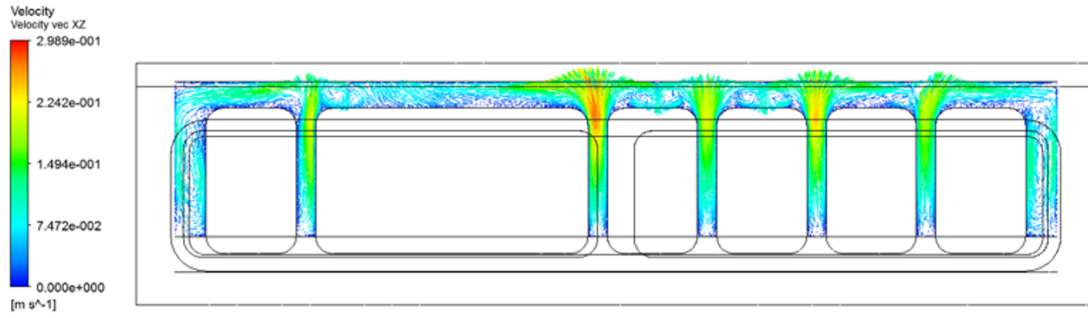


Figure 4.8. Target #3 small-scale prototype: CFD simulation of the nitrogen gas inside the EN AW-6082 T6 vessel.

additional difference between the beam delivered to the n_TOF target and the test beam in the HiRadMat facility is that the maximum possible beam size obtainable in the HiRadMat facility is 4 mm (1σ), while the beam size assumed for the design of the n_TOF Target #3 is 15 mm (1σ). Considering the design value of pulse intensity on Target#3 of $10^{13} p^+$, a first estimation of the equivalent pulse intensity to be used for the beam test can be obtained scaling the pulse intensity by momentum and beam spot area. The two beams give the same energy per unit area over the beam spot:

$$\text{Test pulse intensity (first estimation)} = 10^{13} p^+ \times \frac{20 \text{ GeV}/c}{440 \text{ GeV}/c} \times \left(\frac{4 \text{ mm}}{15 \text{ mm}} \right)^2 = 3.23 \times 10^{10} p^+$$

This first estimation of pulse intensity was used as initial input for FEM thermo-mechanical simulations, which were in turn used to fine tune the pulse intensity (Fig. 4.9). The objective was to obtain a value of stress in the beam test equivalent to the one in Target #3 in terms of total fatigue damage during the entire target lifetime. The equivalent stress was computed applying the *octahedral stress theory* for multiaxial fatigue [79] to the oscillating ranges of principal stresses resulting from simulations. The resulting value of pulse intensity to be used

4.3. Prototype of the nitrogen-cooled lead concept: beam irradiation test

in the beam test to obtain a fatigue stress equivalent to the one in Target #3 was equal to 4.5×10^{10} protons per pulse. The fatigue strength of lead is shown in Fig. 4.10 as a function of number of cycles to failure [60]. The equivalent stress is indicated in Fig. 4.10 for the two cases: 10^8 cycles for the n_TOF Target #3 with the beam load described in Sec. 3.5.1; 1500 cycles for the HiRadMat prototype with the selected pulse intensity of 4.5×10^{10} p⁺ per pulse. According to the adopted criterion, Fig. 4.10 shows that the HiRadMat prototype is subjected to a fatigue damage higher than the one in Target #3, when compared to the fatigue curve.

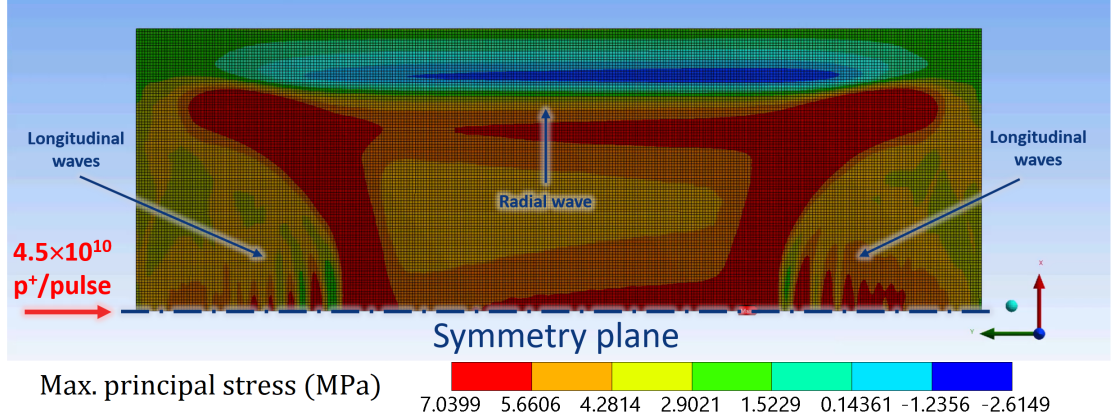


Figure 4.9. Stress-wave propagation in the 150-mm lead block of the HiRadMat beam irradiation test, FEM simulation. The contour plot shows the value of the maximum principal stress. The cut through half model is shown, since the model is symmetrical with respect to the horizontal plane. It is possible to notice the radial and the longitudinal waves.

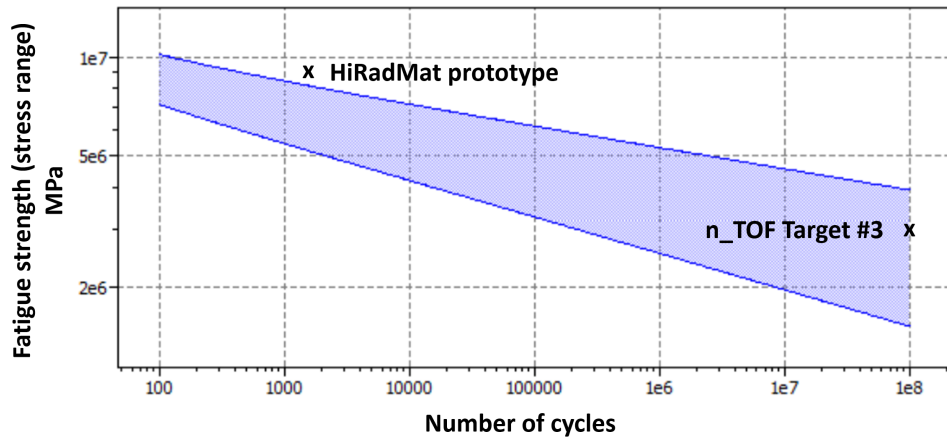


Figure 4.10. Fatigue strength of lead [60]. The stress range to failure ($\sigma_{max} - \sigma_{min}$) is shown for alternating stress (stress ratio $R = -1$). The equivalent stress range estimated by FEM simulations for both the HiRadMat prototype (1500 cycles) and the n_TOF Target #3 (10^8 cycles) is also indicated.

Figure 4.11 shows a plot from the measurements of the thermocouples during the beam irradiation test, confirming that the temperature of the lead blocks was in the desired range. The actual peak temperature reached inside the lead block was about 20°C higher than the one measured on its surface. The graph at the top shows the temperature on the top face of

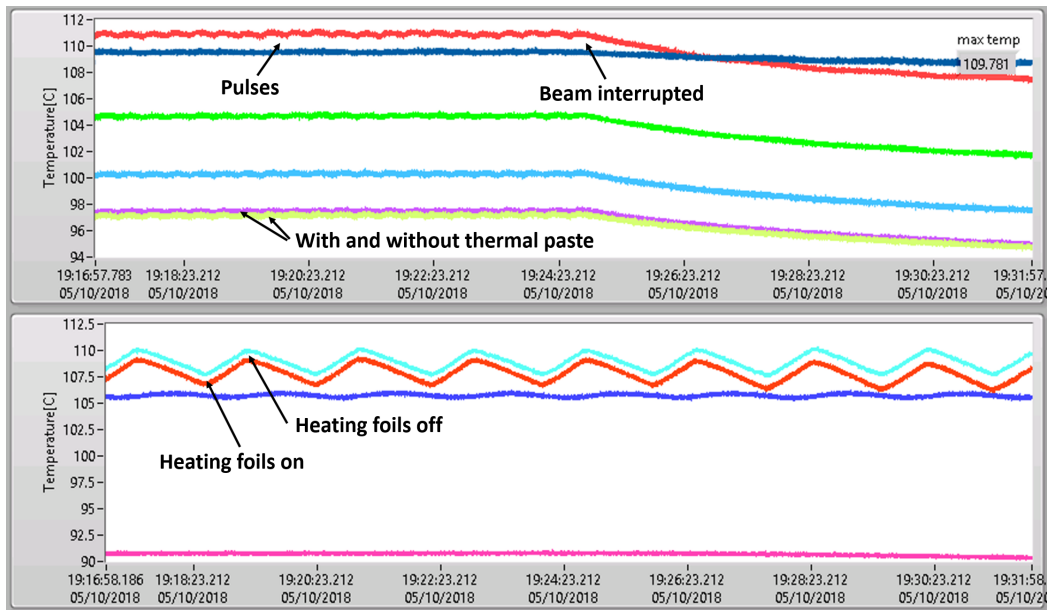


Figure 4.11. HiRadMat beam irradiation test: temperature measurements.

the lead blocks: each small bump in the plots represents one pulse hitting the target. This graph also shows how the temperature decreases when the beam stops hitting the prototype. On the block with two thermocouples, the temperature measurements between the one with thermal paste and the one without differ by less than 1°C. The graph at the bottom shows the measurements of the thermocouples attached to the EN AW-6082 T6 vessel, which are used to control the heating foils switching them on and off to keep the temperature in a specific range.

4.3.1 Post-irradiation examinations

After the beam irradiation test, the lead samples were extracted from the EN AW-6082 T6 vessel in a fume hood. The highest radioactive dose rate measured at contact on the lead surface was 100 $\mu\text{Sv/h}$. Metrology measurements were then performed on the lead blocks, showing a permanent deformation consisting in a protruding bump on the areas of the lead surface impacted by the beam. The largest deformations (up to 115 μm) were measured on the surfaces of the 2nd and 3rd block along the beam direction, which are the blocks with the highest energy density deposited in a single pulse (22 J/cm^3) [80].

The irradiated samples were then observed by means of neutron tomography in the NEUTRA facility at the Paul Scherrer Institut (PSI). Thanks to this imaging technique, it was possible to observe the status of the material inside the lead blocks and detect voids with a resolution of 100 μm . The tomography (Fig. 4.12), showed the inner microstructure of the lead blocks. The tested lead blocks seem intact, and the beam irradiation did not cause detectable voids inside the material.

4.3. Prototype of the nitrogen-cooled lead concept: beam irradiation test

These observations favor the conclusion that the target lead core will be able to keep its functionality and physics performance during the entire target lifetime.

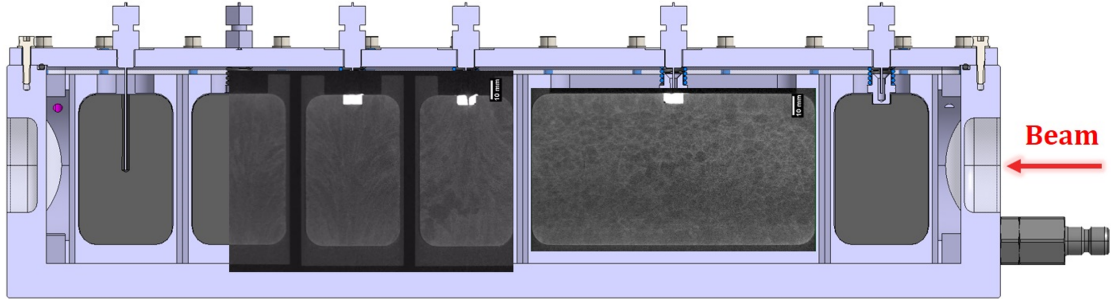


Figure 4.12. Neutron tomography on the lead blocks of the Target #3 prototype irradiated in the HiRadMat facility. The tomography was performed on the blocks from the 2nd to the 5th (along the beam direction), which were the ones subjected to the highest energy deposition. The images from the tomography are superimposed to the CAD model to show their position in the prototype. The white areas visible on top of the blocks are the holes hosting the thermocouples. The tomography did not show any detectable void inside the lead blocks.

The external surfaces of the lead blocks were also subjected to Brinell hardness measurements (Fig. 4.13). The values measured are typical of the unhardened material, even if hardening would be expected because of the high stresses caused by stress-wave propagation (Fig. 4.9). This observation may be explained by the proclivity of pure lead to 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 (between 100 and 140°C) [62, 76].

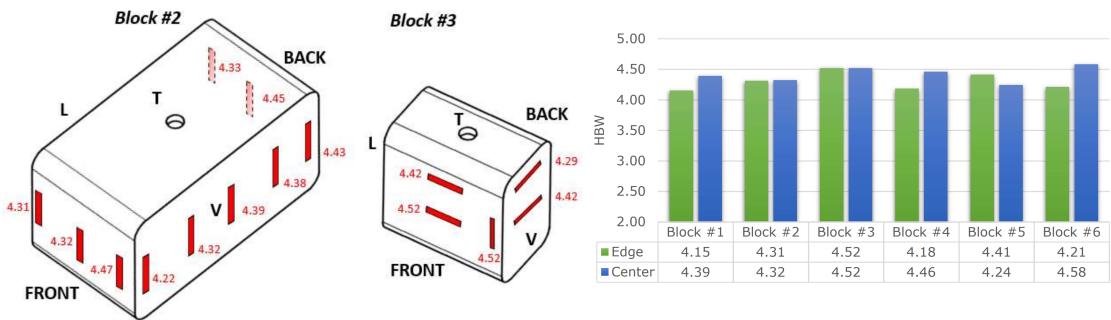


Figure 4.13. Hardness measurements on the lead blocks of the Target #3 prototype irradiated in the HiRadMat facility. The differences in the measured values are not statistically relevant and are typical of the unhardened material.

Uniaxial tests were performed on pure lead specimens to estimate the extent of these effects. The specimens were subjected to strain-controlled load cycles followed by a period where the maximum strain was held constant. These and other mechanical characterization tests performed on pure lead for this work are described in detail in Chap. 5. One example is reported in Fig. 4.14: the material was cyclically loaded between a strain of 1.5% in tension and 1.5% in compression, at a strain-rate of 0.1 s^{-1} . In this stage, the material cyclically hardened until a plateau was reached at 15 MPa after 120 cycles. The specimen was held in tension at

the maximum strain of 1.5% for 20 minutes. The time evolution of the measured stress shown in Fig. 4.14 reveals how, already at room temperature, the 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).

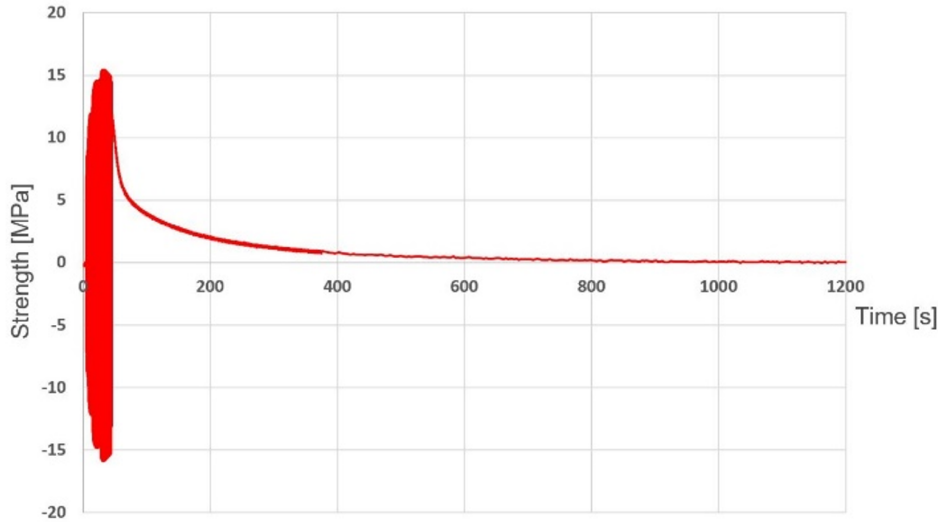


Figure 4.14. Strain-controlled cyclic tests performed on pure lead specimens: the material was cyclically loaded between a strain of 1.5% in tension and 1.5% in compression, at a strain-rate of 0.1 s^{-1} , for 120 cycles. The specimen was then held in tension for 20 minutes. The material cyclically hardens until a plateau of 15 MPa is reached, then the measured stress decays while the maximum strain is held constant.

4.4 Prototype of the Ti-6Al-4V-clad lead concept: beam irradiation test

To manufacture the Ti-6Al-4V-clad Pb prototype, a $\varnothing 150 \times 300 \text{ mm}^2$ pure lead cylinder was pressed inside a Ti-6Al-4V 1.5-mm-thick tube (Fig. 4.15). The tube is closed by welding two Ti-6Al-4V lids at its ends. The thickness of the Ti-6Al-4V lids could not be larger than 0.5 mm to not increase the background. Such a thin layer of Ti-6Al-4V would undergo large deformations as soon as it is pushed by the expanding lead core because of thermal expansion. Figure 4.17 shows a FEM simulation where, even with a Ti-6Al-4V lid's thickness as large as 2 mm, the deformation due to pressure from the lead core is large enough to create a gap between the lead surface and the Ti-6Al-4V lid, suppressing the thermal conductance between the two elements.

Two beryllium discs (16-mm thick) have been added to the prototype at its ends to add stiffness to support the Ti-6Al-4V lids (Fig. 4.15). Thick layers of pure beryllium rather than Ti-6Al-4V can be added to the target since beryllium is one of the few materials that does not increase background or decrease physics performance. A complication of this solution consists in the

4.4. Prototype of the Ti-6Al-4V-clad lead concept: beam irradiation test



Figure 4.15. Manufacturing process of the prototype of the Ti-6Al-4V-clad lead target concept. Left: a pure-lead cylinder was inserted into a Ti-6Al-4V tube. Center: a beryllium disc was added at each end of the lead cylinder. Right: a Ti-6Al-4V thin lid was placed at each end of the tube and the whole assembly was compressed, with a pressing tool, to deform the lead cylinder and increase the contact pressure between the parts of the assembly. The Ti-6Al-4V lids were finally welded by electron-beam welding to encapsulate the entire assembly in a Ti-6Al-4V envelope.

addition of two new interfaces: good thermal contact must now be ensured at the Pb-Be and Be-Ti interfaces. A solution providing a good mechanical contact is presented below. According to the theory of thin plates and assuming small displacements, the deformation of a thin plate subject to a certain axisymmetric pressure distribution follows a fourth-order polynomial curve along the radial direction. The analytical solution for any pressure distribution that can be described by a second-order polynomial piecewise function of the radial distance from the center of the plate is available [81]. Once the desired pressure distribution is imposed, it is possible to compute the resulting deformation of the thin Ti-6Al-4V lid. Similarly, imposing such a deformation would yield the desired pressure profile as a reaction. Such deformation can actually be imposed to the Ti-6Al-4V thin lids of the prototype by machining accordingly the surface of the beryllium plates file and indent them into the lids. The beryllium plates would deform the thin Ti-6Al-4V lids according to the computed shape and, as a reaction, the thin Ti-6Al-4V lids would push on the beryllium plates generating the desired profile of contact pressure. The imposed pressure profile is shown in Fig. 4.16 and is described by the following function, with the radial coordinate r ranging from 0 at the centre of the lid to 58 mm at the border of the interface area between beryllium and Ti-6Al-4V:

$$p(r) = \begin{cases} -\frac{p_{max}}{aR} (r^2 - aR) & 0 \leq r \leq a \\ \frac{p_{max}}{R(R-a)} (r^2 - 2Rr + R^2) & a < r \leq R \end{cases} \quad (4.1)$$

Where:

$p(r)$: desired pressure profile

p_{max} : peak desired pressure at the center of the lids

R : radius of the interface between the Ti-6Al-4V lids and the beryllium plates (58 mm)

a : radius where the transition between the two second-order polynomials is located (14.5 mm)

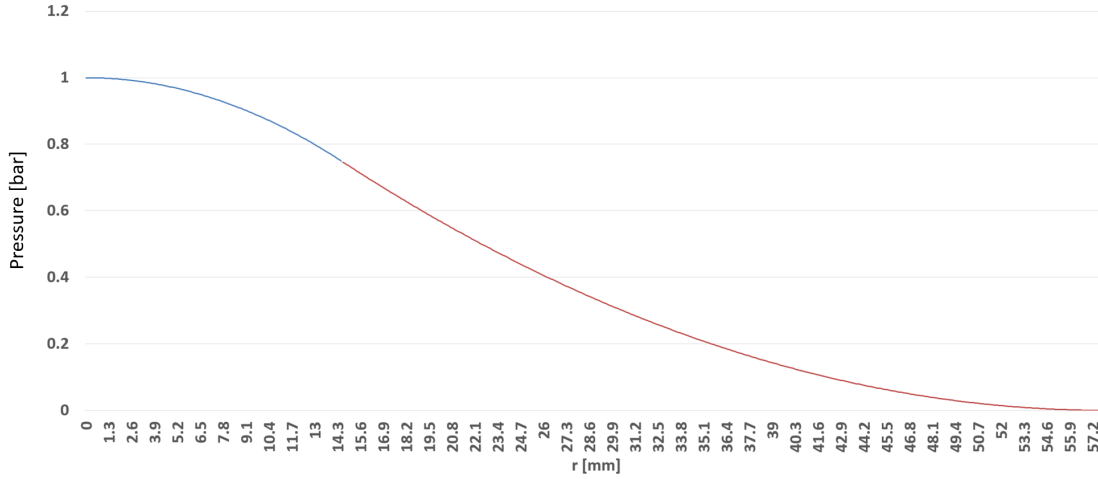


Figure 4.16. Profile of the desired pressure at the contact interface between the beryllium plates and the Ti-6Al-4V lids.

The two second-order polynomials were chosen so that:

- the pressure profile $p(r)$ and its first derivative $p'(r)$ are continuous everywhere
- $p(0) = p_{max}$: the highest pressure is located at center of the lid to have the highest thermal contact conductance around the axis of the proton beam, where the highest temperature is reached
- $p'(0) = 0$: the pressure profile $p(r)$ is flat in the center
- $p(R) = 0$ and $p'(R) = 0$: the pressure decreases to zero at the edge of the interface
- they have the same value and slope for $r = a$
- $p_{max} = 1$ bar to induce a maximum deformation of the lids of 1.5 mm

A more accurate estimate of the deformation to be imposed to the Ti-6Al-4V, taking into account the deviation from the small displacement assumption, was obtained by performing a FEM simulation inclusive of the effects of large deformations. The displacement field thus obtained was fitted by a sixth-order polynomial, which was given as input to the lathe machining the beryllium plate (Fig. 4.18). The indentation of the beryllium plate into the

4.4. Prototype of the Ti-6Al-4V-clad lead concept: beam irradiation test

Ti-6Al-4V lid was then simulated with the FE method, confirming that the desired contact pressure could be achieved by using the described approach (Fig. 4.19).

Once the Ti-6Al-4V lids are welded, the pressure from the lead cylinder would induce bending stress on the lids and localized tensile stresses at the end of the welding seam (left of Fig. 4.20), risking to damage it. To overcome this problem, an additional ring-shaped component was added before welding the lids. As can be seen from the right part of Fig. 4.20, the shape of the added ring is such that it exerts a force on the lid inducing on the weld a bending moment of opposite sign than the one caused by the pressure from the lead cylinder and the beryllium plate. Figure 4.21 shows a FEM simulation of the indentation of the beryllium plate into the Ti-6Al-4V lid: the lid is deformed to match the beryllium surface perfectly, while the stresses in the weld area are no longer tensile, but compressive. The expansion of lead induces then, as an end result, the closure of the the notch at the end of the welding seam rather than its opening.

The Ti-6Al-4V-clad lead prototype was irradiated in the HiRadMat facility by 1000 pulses of $3.6 \times 10^{12} \text{ p}^+$. This pulse intensity is 80 times higher than the one used for the bare-lead

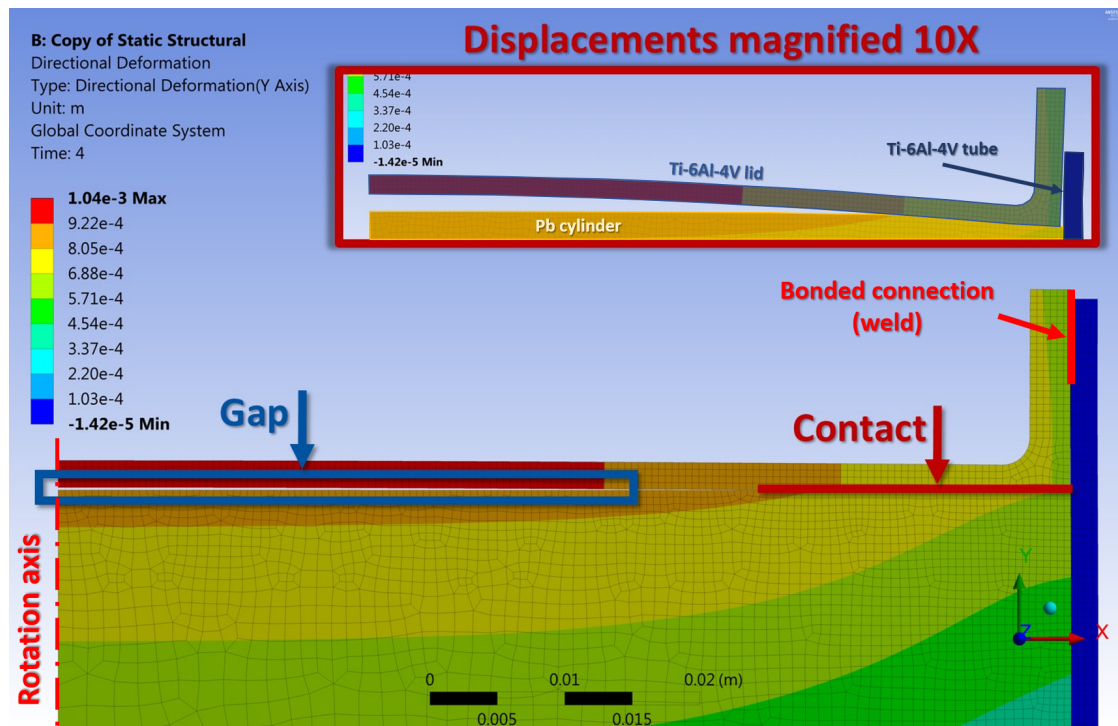


Figure 4.17. FEM simulation of a Ti-6Al-4V-clad pure-lead cylinder. The model is two-dimensional and axisymmetric. The Ti-6Al-4V lid (2-mm thick) is initially pressed onto the lead cylinder ($\varnothing 150 \text{ mm}$) using a hydraulic press and then welded to the Ti-6Al-4V tube (the weld was modelled by activating a *bonded* contact). When the pressure generated by the hydraulic press is removed, the Ti-6Al-4V lid is free to deform under the pressure coming from the lead cylinder. The deformation is such that a gap is created between the Ti-6Al-4V lid and the lead cylinder such that efficient heat transfer is compromised.

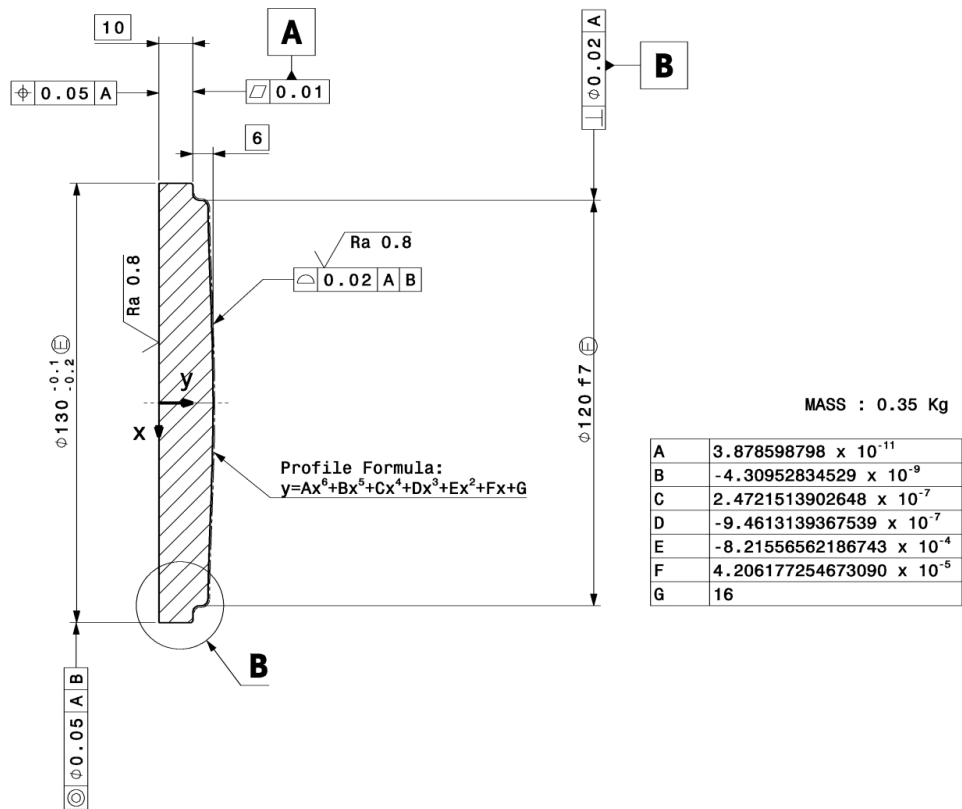


Figure 4.18. Technical drawing of the beryllium plates for the Ti-6Al-4V-clad lead prototype (dimensions in mm). The drawing shows the sixth-order polynomial calculated to obtain the desired contact pressure profile.

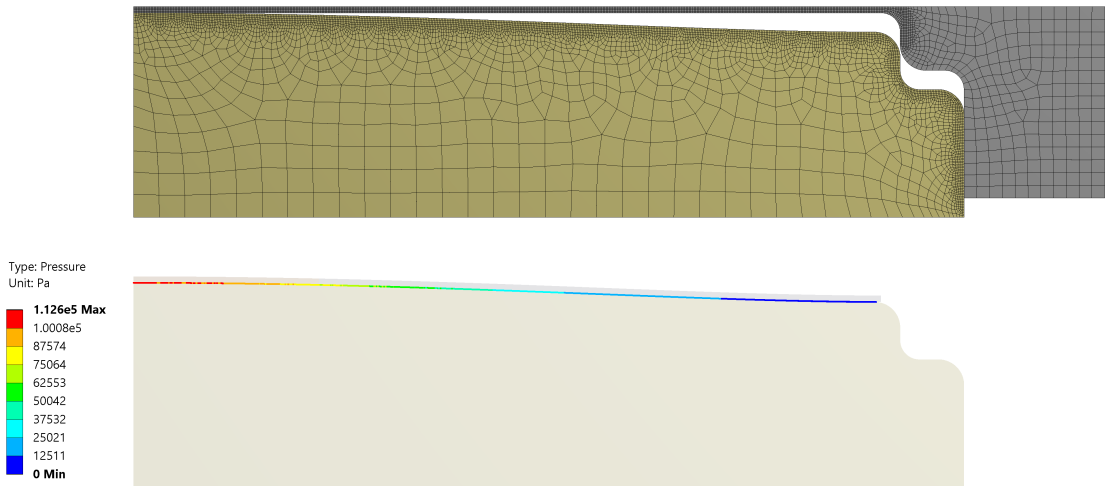


Figure 4.19. FEM simulation of the indentation of the beryllium plate into the Ti-6Al-4V lid. Top: 2D axisymmetric model of the beryllium plate and the Ti-6Al-4V lid. The model shows the initial position before indentation of the beryllium plate into the Ti-6Al-4V lid. Bottom: result of the simulation after indentation. The plot shows the pressure at the contact interface.

4.4. Prototype of the Ti-6Al-4V-clad lead concept: beam irradiation test

prototype. The aim of this beam-irradiation test was to assess the ability of the Ti-6Al-4V container to keep its integrity even in case of lead melting and no constraint on the beam power deposited in the target. The energy needed to raise lead temperature from room temperature to its melting point (327°C) and melt it is 65 kJ/kg, while the peak energy deposition reached by a single pulse in this beam irradiation experiment was 145 kJ/kg.

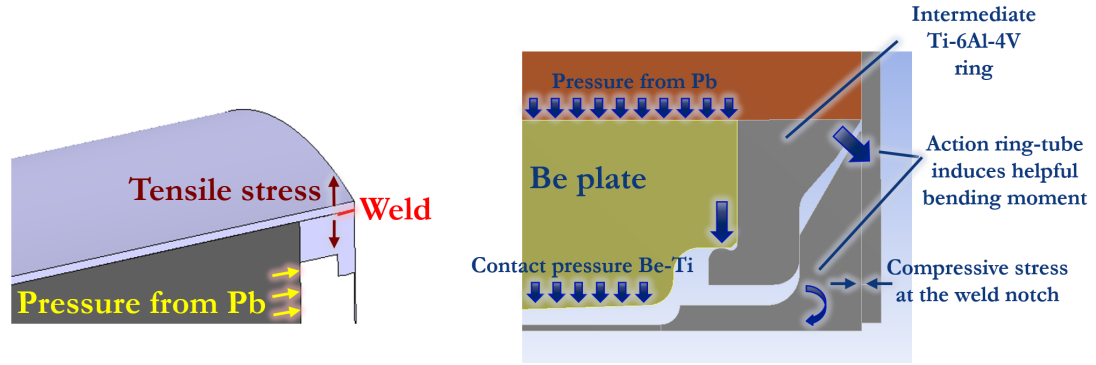


Figure 4.20. Left: the pressure from the lead cylinder acts on the beryllium plate which, in turn, pushes the Ti-6Al-4V lid. This action induces a bending moment, on the weld between the Ti-6Al-4V lid and the tube, that opens the weld and provokes tensile stresses at the end of the welding seam. Right: an additional Ti-6Al-4V ring can move the point of force application on the Ti-6Al-4V so as to induce a bending moment of opposite sign that closes the weld instead of opening it.

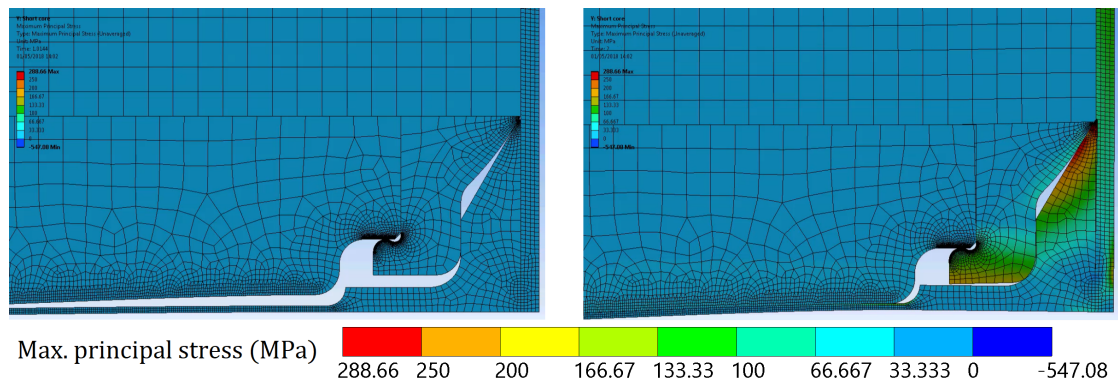


Figure 4.21. FEM simulation of the indentation of the beryllium plate into the Ti-6Al-4V lid. Left: initial configuration with lid welded on the Ti-6Al-4V tube. Right: the lead cylinder expands and the lid is deformed to match the beryllium surface perfectly, while the stresses in the weld area are no longer tensile, but compressive. The contour plot shows the value of the maximum principal stress. The expansion of lead induces then, as an end result, the closure of the the notch at the end of the welding seam rather than its opening.

4.4.1 FEM simulations of beam impact

Figure 4.22 shows a FEM simulation of the Ti-6Al-4V-clad lead prototype impacted by a proton beam pulse during the test in the HiRadMat facility. Also in this case, the simulation shows the

typical propagation of longitudinal and radial stress waves in lead. The three points with the highest stress values are highlighted. Figure 4.23 shows the evolution of the three principal stresses in the three points highlighted in Fig. 4.22 during the first 100 μs after the beam pulse impact. A first remark is that, for all the three points, the curves of the three principal stresses match almost perfectly, which means that the state of stress in all the three points is mainly hydrostatic. The highest stress is reached in point 1, located just below the base surface of the lead cylinder where the beam is impacted. During the beam impact the heat deposition, the rapid rise in temperature, and the constrained thermal expansion induces the high compressive stress visible in the plot of points 1 and 3. The highest compressive stress is equal to 519 MPa and is reached in point 3. Because of inertia effects, a tensile wave (the longitudinal wave shown in Fig. 4.22) starts to propagate along the axial direction from the cylinder base inducing the tensile-stress spike in point 1, 6 μs after the beam impact. This is the highest value of tensile stress in lead observed in the simulation, equal to 306 MPa. Another spike in tensile stress (122 MPa) is observed in the plot of point 3 and is related to the propagation of a cylindrical wave starting from the beam axis. This wave propagates radially until it reaches point 2 in Fig. 4.22 after 35 μs and is reflected after reaching the cylindrical surface of the lead part. The transit of the wave below the cylindrical surface is visible in the plot of point 2 as a violent stress oscillation from 35 μs to 56 μs : the stress goes rapidly from 43 MPa in compression to 67 MPa in tension. Finally, the reflected radial wave propagate back to the cylinder axis with a new tensile-stress spike (up to 188 MPa in tension) visible in the plot of point 3 at 90 μs .

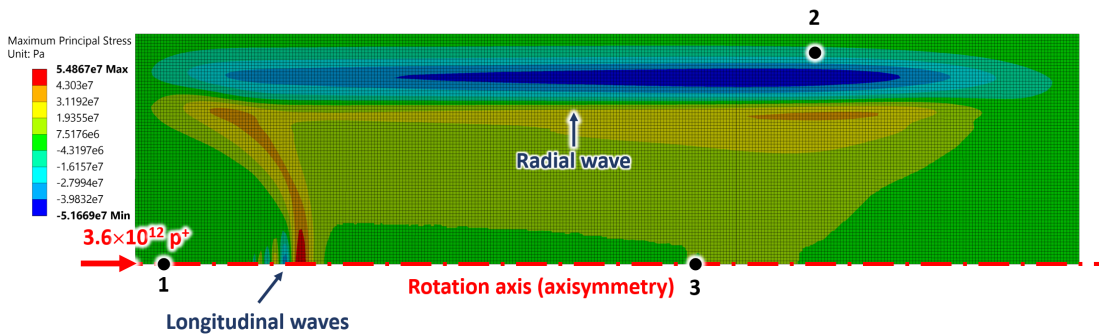


Figure 4.22. FEM simulation of the Ti-6Al-4V-clad lead prototype impacted by a proton beam pulse during the beam irradiation test in the HiRadMat facility. The image shows the propagation of longitudinal and radial stress waves. The three points with the highest stress values are highlighted and their stress history is shown in Fig. 4.23.

The maximum stress and stress amplitude in the Ti-6Al-4V are 153 MPa and 194 MPa, respectively, and are located in the upstream lid. The maximum stress and stress amplitude in the beryllium plates are 75 MPa and 98 MPa, respectively, and are located in the upstream beryllium plate. These values are acceptable according to the limit values shown in Table 2.15.

4.4. Prototype of the Ti-6Al-4V-clad lead concept: beam irradiation test

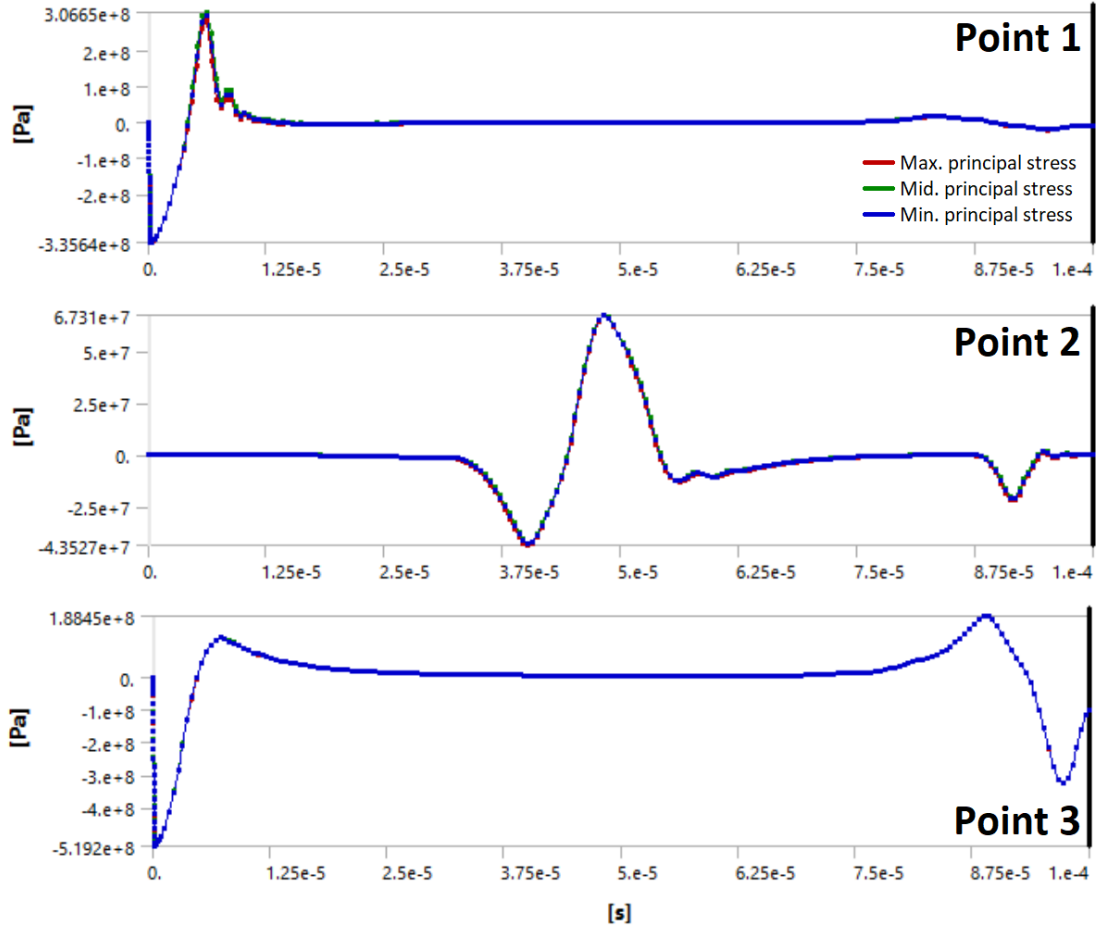


Figure 4.23. Evolution of the three principal stresses in the three points highlighted in Fig. 4.22 during 100 μ s after the beam impact. The stress-state is mainly hydrostatic, with the three principal stresses matching almost perfectly. The violent stress oscillations visible in all the three plots are related to the passage of stress waves propagating in the material.

4.4.2 Post-irradiation examinations

After being irradiated with 1000 pulses of $3.6 \times 10^{12} \text{ p}^+$, the prototype was left untouched for almost three years to let the radioactive dose-rate decrease. The Ti-6Al-4V-clad Pb core was then extracted from its stainless steel vessel and observed by neutron tomography. The maximum radioactive dose-rate measured at this stage on the surface of the Ti-6Al-4V container was equal to 50 $\mu\text{Sv/h}$ and located on the beam impinging spot. The neutron tomography was performed at the *Institute Laue-Langevin* in Grenoble.

A cut view obtained by postprocessing the neutron tomography data is shown in Fig. 4.24. The tomography shows that the proton beam damaged the lead cylinder to the point of forming a hole through almost the entire length of the cylinder, where the energy deposition and the stresses due to stress-wave propagation were the highest (see Sec. 4.4.1). The diameter of the hole is, for most of its length, about 1 cm.

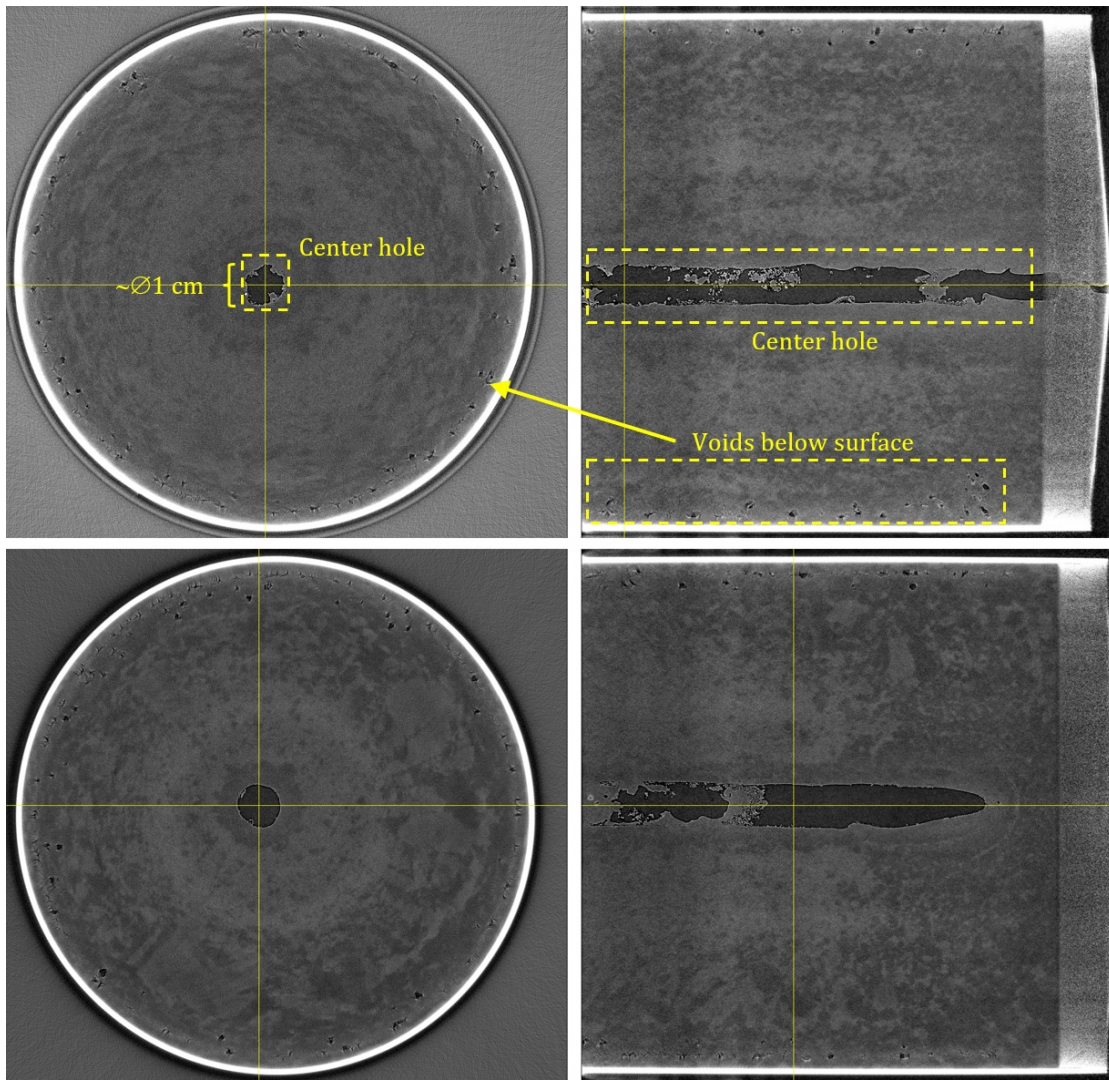


Figure 4.24. Neutron tomography of the Ti-6Al-4V-clad Pb prototype tested under beam irradiation in the HiRadMat facility. The resolution of the tomography is 100 μm . Top: section cut of the upstream half of the prototype. Bottom: section cut of the downstream half of the prototype. The proton beam damaged the lead cylinder forming a $\sim \text{Ø}1$ cm hole through almost its entire length. Many voids have also been formed below the cylindrical surface, probably caused by the reflection of radial stress-waves after each proton beam impact.

In addition, many voids have been formed below the cylindrical surface. This can be explained with the fact the highest stress values, outside of the region around the cylinder axis, are reached below the cylindrical surface because of the radial-wave reflection and the stress spike shown in the plot for point 2 in Fig. 4.23.

The neutron tomography also revealed radial cracks in the upstream beryllium plate (Fig. 4.25). Since the hole in the lead cylinder is relatively large compared to the beam size (about 25% larger than 1σ of the beam size), the downstream beryllium plate was subjected at some point to an energy deposition similar to the upstream plate; nonetheless, the downstream plate did

4.4. Prototype of the Ti-6Al-4V-clad lead concept: beam irradiation test

not crack. This, in addition to FEM simulations showing an acceptable stress in the beryllium plate, supports the hypothesis that the upstream beryllium plate was not damaged primarily by the direct beam impacts, but by the bending stress induced by the new shape adopted by the lead part. Once the upstream plate failed, the load induced on both plates from the lead part was reduced, leaving the downstream plate intact.

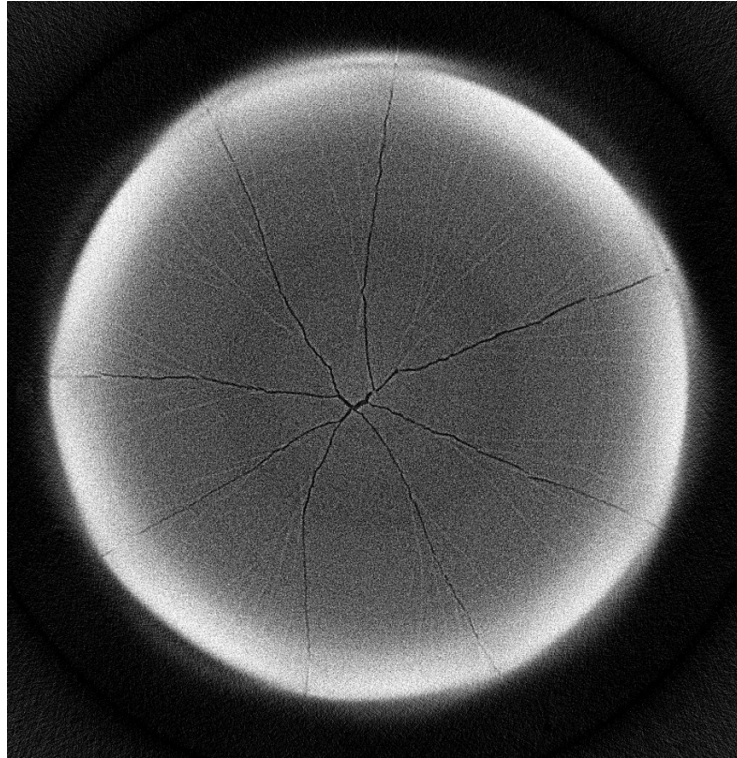


Figure 4.25. Neutron tomography of the Ti-6Al-4V-clad Pb prototype tested under beam irradiation in the HiRadMat facility: radial cracks in the upstream beryllium plate.

Even with such an extreme load case, leading to extensive damage of the lead core and one of the two beryllium plates, the Ti-6Al-4V layer remained intact and its content sealed. This encourages the use of such an alloy as a cladding material if preventing leakage of toxic and radioactive core materials, even under unexpectedly heavy loads, is of primary importance. The neutron tomographies showed, on the other hand and despite being limited, that the lead core can still get damaged and deform so as to develop a large hole around the beam axis. The axial hole volume can easily be compensated by the elastic expansion of the Ti-6Al-4V cladding. This leads to the conclusion that even a clad target solution would require a limitation of the beam intensity, since the formation of a hole around the beam axis would result in a critical reduction of the beam-lead interaction and the neutron production.

5 Mechanical characterization and modelling of pure lead

5.1 Introduction

The previous chapters described the thermo-mechanical response of the pure lead core of the n_TOF Target #3. To obtain a useful feedback from Finite Element simulations, such as those presented in this work, it is important to identify the main features of pure lead stress-strain response and include them in the constitutive model. In the previous chapters it has been described how the interaction between proton beam and lead target induces a rapid heat production leading to propagation of stress waves. These loads induce a multiaxial stress-state and cyclic plasticity in the lead core. The most popular methods to model multiaxial plastic behavior of ductile materials, such as pure lead, are based on *incremental plasticity* theories [51, 52, 77, 82].

The plasticity model used in the simulations presented in this work to reproduce multiaxial cyclic plasticity in lead is the *multilinear isotropic hardening* model [83, 84]. This model has the advantage of being defined simply by a monotonic stress-strain curve, such as those obtained by uniaxial tests. The curve can be discretized as a piecewise function of the total strain (Fig. 5.1). The first stress-strain point corresponds to the yield stress. Subsequent points define the elastic-plastic response of the material.

The yield surface is described, in the stress space, by the von Mises criterion [77]. In this case, it takes the shape of a cylinder with radius $\sqrt{\frac{2}{3}}\sigma_y(\epsilon)$:

$$\sqrt{\boldsymbol{\sigma} : \boldsymbol{\sigma} - \frac{1}{3} \text{Tr}(\boldsymbol{\sigma})^2} - \sqrt{\frac{2}{3}}\sigma_y(\epsilon) \leq 0 \quad (5.1)$$

Where:

$\boldsymbol{\sigma}$: stress tensor

$\sigma_y(\epsilon)$: stress-strain curve

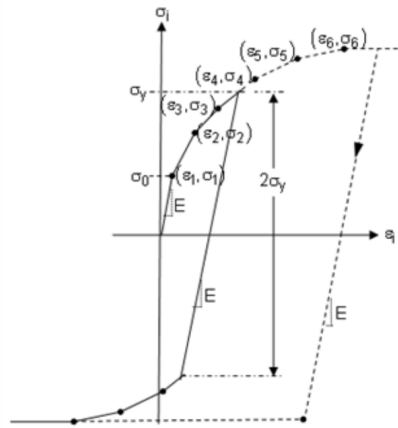


Figure 5.1. The *multilinear isotropic* hardening model can be defined simply by a uniaxial stress-strain curve. The curve can be discretized as a piecewise function of the total strain. The first stress-strain point corresponds to the yield stress. Subsequent points define the elastic-plastic response of the material [83].

This model is included in many FEM software packages because it is very practical, as it only requires defining a monotonic stress-strain curve of the material obtainable with a conventional tensile test. However, it is not capable of reproducing more complex effects of the material behaviour arising in multiaxial cyclic plasticity conditions. Moreover, it has a limited application in the prediction of the actual state of the material after millions of load cycles with a complex load history, as seen in Sec 3.5.2. Some of these effects are described in the following sections, where the utilization of a more advanced model is proposed. The proposed model requires the identification of additional material parameters and the execution of cyclic mechanical tests.

5.2 Mechanical tests under cyclic plasticity

The hardening behaviour in pure lead, when subjected to cyclic plasticity, depends on the load history. A campaign of strain-controlled cyclic uniaxial tests has been carried out on pure-lead specimens to observe the stress-strain response of the material when subjected to cyclic plasticity. The tests were performed by the Department of Mechanical and Industrial Engineering of the Norwegian University of Science and Technology (NTNU) and SINTEF Industry in Trondheim (Norway).

The tests consisted in strain-controlled load cycles in tension and compression. The specimens were cyclically deformed over the following strain ranges: $\pm 0.25\%$, $\pm 0.5\%$, $\pm 1\%$, and $\pm 1.5\%$. In a single test, each specimen was cyclically loaded over all the ranges, starting from the smallest and progressively increasing towards higher values of strain. The specimens were loaded for 20 cycles for each strain range.

Figure 5.2 shows the geometry of the specimens and a photo of a specimen mounted on the

test bench. Because of the creep effects in lead described in Chap. 3, the specimen holding jaws were equipped with springs to ensure the needed grip throughout the test. The strain controlling the applied load was measured by an extensometer mounted on the specimen.

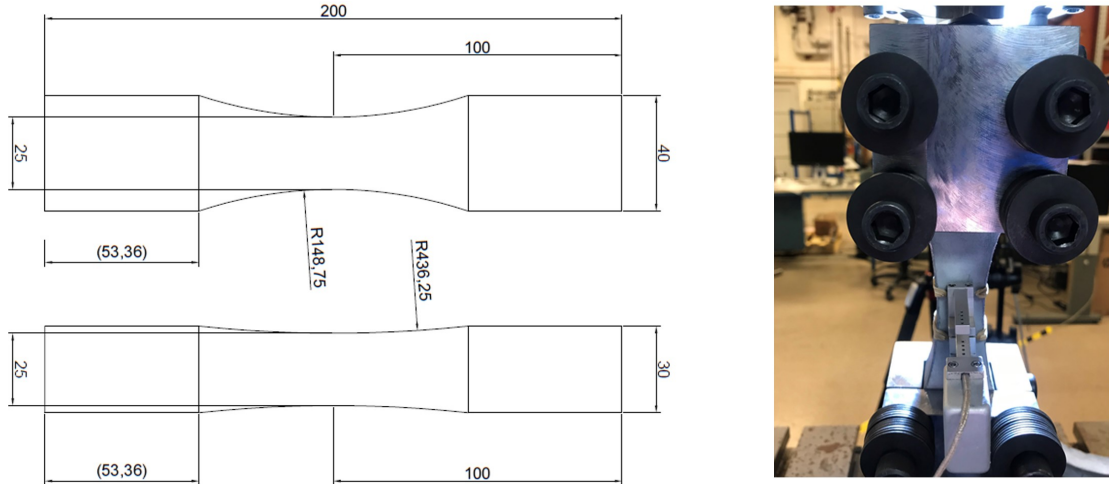


Figure 5.2. Left: geometry of the pure lead specimens used for the mechanical characterization campaign under cyclic loading (dimensions in mm). Right: a pure lead specimen mounted on the test bench. Because of the creep effects in lead described in Chap. 3, the specimen holding jaws are equipped with springs to ensure the needed grip throughout the test. The strain controlling the applied load was measured by an extensometer mounted on the specimen.

The tests were performed at 20°C, 90°C, and 150°C using a thermal chamber. These temperatures cover the range of operation of the n_TOF Target #3. Two levels of strain rate were tested: 10^{-2} and 10^{-1} s^{-1} . Higher values may be reached in Target #3 because of the dynamic response of the target when impacted by a beam pulse, but it was not possible to perform reliable cyclic tests at higher strain-rates. At the end of each test, after the last cycle ending with the maximum tensile strain of +1.5%, the strain was held for 20 minutes to measure stress relaxation and hardening recovery. A summary of results of the tests performed is presented in Fig. 5.3.

Figure 5.3 clearly shows the temperature dependence of the cyclic curves: higher temperature corresponds to lower strength. The strain-rate dependence seems to have a limited effect at room temperature, with a maximum measured force of 10 kN (16 MPa) in both cases. The strain-rate dependence appears more relevant at higher temperatures, with higher strength at higher strain rate. The symmetry of the curves with respect to the horizontal axis shows that pure lead exhibits the same stress-strain behaviour in tension and in compression. The curvature observable after the linear part at each cycle, both in tension and in compression, reveals that the material is subject to the Bauschinger effect: yielding in tension causes a reduction of the yield stress in compression and vice versa, typical of kinematic hardening. The material also exhibits a cyclic-hardening behaviour: its strength increases asymptotically cycle after cycle towards a maximum value. It is evident, from Fig. 5.3, that this maximum value depends on the strain range: an effect known as *non-Masing* behaviour.

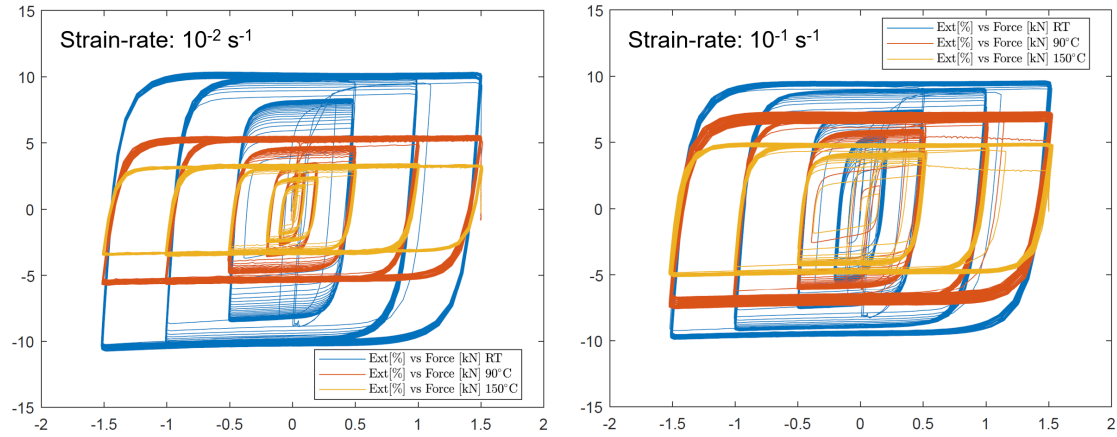


Figure 5.3. Pure lead cyclic curves. The tests were performed by the Department of Mechanical and Industrial Engineering of the Norwegian University of Science and Technology (NTNU) and SINTEF Industry in Trondheim (Norway). The comparison between curves obtained in different test conditions shows the temperature and strain-rate dependence of the material behaviour. The material exhibits Bauschinger effect, cyclic-hardening behaviour, and non-Masing behaviour.

5.3 Material model for cyclic plasticity

In this section, an incremental plasticity model is proposed to represent the behaviour of pure lead when subjected to cyclic plasticity. The model aims to reproduce the Bauschinger effect, the cyclic hardening behaviour, and the non-Masing behaviour. The material response at different temperatures can be modelled by identifying independently the model parameters with respect to different test results and interpolate their values making them temperature-dependent. As in most incremental plasticity models, the first pieces defining the model are the additive decomposition of the strain tensor and the Hooke's law [52]:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p + \boldsymbol{\varepsilon}^{th} \quad (5.2)$$

$$\boldsymbol{\sigma} = \mathbb{E} : \boldsymbol{\varepsilon}^e \quad (5.3)$$

where:

$\boldsymbol{\varepsilon}$: total strain tensor

$\boldsymbol{\varepsilon}^e$: elastic strain tensor

$\boldsymbol{\varepsilon}^p$: plastic strain tensor

$\boldsymbol{\varepsilon}^{th}$: thermal strain tensor

$\mathbb{E}$: fourth-order elastic stiffness tensor

The von Mises criterion is adopted to define the yield surface. To model the Bauschinger effect, kinematic hardening behaviour is included by adding a backstress tensor $\mathbf{X}$ to the yield surface. The cyclic plasticity effects are included by adding an isotropic hardening variable R [51]:

$$f = \sqrt{\frac{3}{2} (\boldsymbol{\sigma}' - \mathbf{X}) : (\boldsymbol{\sigma}' - \mathbf{X})} - R - \sigma_{y0} = 0 \quad (5.4)$$

where $\boldsymbol{\sigma}'$ is the deviatoric stress tensor and σ_{y0} is the initial value of the yield stress. The backstress $\mathbf{X}$ is related to the position of the yield surface in the stress space, while $\sigma_{y0} + R$ is related to its size. In the case of the von Mises criterion, the yield surface is a cylinder in the space of principal stresses and its axis is parallel to the hydrostatic axis. The backstress $\mathbf{X}$ is then related to the position of the axis in the principal stress space, while $\sigma_{y0} + R$ is related to the radius of the cylinder.

The plastic strain rate is defined by an *associative flow rule*, which means that the plastic strain rate tensor is proportional to $\mathbf{N}$, the normal to the flow surface. λ is also called *plastic multiplier* [82]:

$$\dot{\boldsymbol{\epsilon}}^p = \dot{\lambda} \mathbf{N} = \dot{\lambda} \frac{\frac{3}{2} (\boldsymbol{\sigma}' - \mathbf{X})}{\sqrt{\frac{3}{2} (\boldsymbol{\sigma}' - \mathbf{X}) : (\boldsymbol{\sigma}' - \mathbf{X})}} \quad (5.5)$$

$$\dot{\lambda} = \sqrt{\frac{2}{3} \dot{\boldsymbol{\epsilon}}^p : \dot{\boldsymbol{\epsilon}}^p} \quad (5.6)$$

The Armstrong-Frederick kinematic hardening model is adopted to describe the evolution of the backstress $\mathbf{X}$ [77]. A similar model is adopted to model the cyclic hardening effects by the isotropic hardening variable R :

$$\dot{\mathbf{X}} = \frac{2}{3} C \dot{\boldsymbol{\epsilon}}^p - \gamma \mathbf{X} \dot{\lambda} \quad (5.7)$$

$$\dot{R} = b (Q - R) \dot{\lambda} \quad (5.8)$$

C , γ , b , and Q are parameters that must be identified by fitting the experimental curves.

To model the variation of the stabilized cycle with the strain range, an additional state variable must be included. The parameter Q in Eq. 5.8, representing the asymptotic value of the variable R related to cyclic hardening, is no longer constant but depends on the maximum strain range reached. A way to model this behaviour is represented by the *strain memory*

model proposed in [85]. A new limit surface is introduced in the space of plastic strains:

$$F = \sqrt{\frac{2}{3}} (\boldsymbol{\varepsilon}^P - \boldsymbol{\zeta}) : (\boldsymbol{\varepsilon}^P - \boldsymbol{\zeta}) - q = 0 \quad (5.9)$$

Similar to the yield surface in Eq. 5.4, as long as the tensor of plastic strain stays 'inside' the limit surface ($F \leq 0$), the surface does not change. When the tensor of plastic strain is on the surface and the flow occurs in the direction external to it ($F = 0$ and $\dot{F} > 0$, material deformed towards higher values of strain), the limit surface and the variables defining it ($\boldsymbol{\zeta}$ and q) evolve according to the following laws:

$$\dot{q} = \frac{1}{2} (\mathbf{N} : \mathbf{n}^*) \dot{\lambda} \quad (5.10)$$

$$\dot{\boldsymbol{\zeta}} = \frac{1}{2} (\dot{\boldsymbol{\varepsilon}}^P : \mathbf{n}^*) \mathbf{n}^* \quad (5.11)$$

where $\mathbf{n}^*$ is the normal to the 'strain memory' surface F :

$$\mathbf{n}^* = \frac{\sqrt{\frac{2}{3}} (\boldsymbol{\varepsilon}^P - \boldsymbol{\zeta})}{\sqrt{\frac{3}{2}} (\boldsymbol{\varepsilon}^P - \boldsymbol{\zeta}) : (\boldsymbol{\varepsilon}^P - \boldsymbol{\zeta})} \quad (5.12)$$

Similarly to the $\mathbf{X}$ and R variables for the yield surface in Eq. 5.4, the variables $\boldsymbol{\zeta}$ and q are related to the position and the radius of the strain memory surface in Eq. 5.9, respectively.

The dependence of the asymptotic value of the cyclic hardening Q (Eq. 5.8) on the reached strain range can then be included through the variable related to the size q of the strain memory surface (Eq. 5.9):

$$Q = Q_M - (Q_M - Q_0) e^{-2\mu q} \quad (5.13)$$

where Q_M and Q_0 and μ are parameters to be identified by fitting the model to the experimental curves.

5.4 Application of the material model for cyclic plasticity to pure lead

As a demonstration of the ability of the proposed model to reproduce the behavior of pure lead when subjected to cyclic loading, an application of the model to a cyclic test is presented below.

5.4. Application of the material model for cyclic plasticity to pure lead

The test consisted of 125 tension-compression cycles over five strain-range intervals: 0.25%, 0.5%, 0.75%, 1%, and 1.5%. Each strain range was tested for 25 cycles. The test was carried out at room temperature and with a strain rate of 10^{-2} s^{-1} .

Figure 5.4 shows a comparison between the experimental data and the stress-strain curves computed using the proposed model, obtained by numerical integration of equations 5.2 to 5.13 for the case of uniaxial loading.

The values of the model parameters used for this comparison are shown in Table 5.1.

Table 5.1. Values of the parameters of the proposed cyclic plasticity model used to reproduce the experimental curves in Fig. 5.4.

Parameter	Value
Young's modulus E	14 GPa
Initial yield strength σ_{y0}	2 MPa
C	6000 MPa
γ	1500
b	2
Q_M	6.23 MPa
Q_0	1.54 MPa
μ	123.4

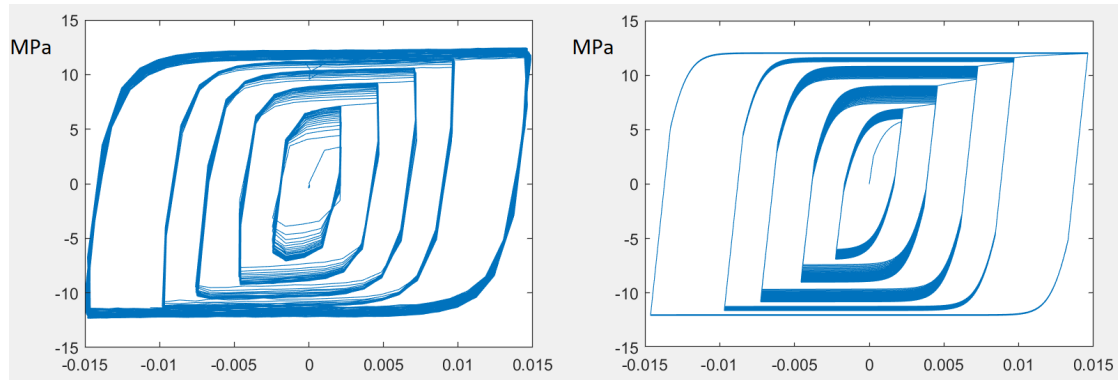


Figure 5.4. Uniaxial cyclic tests on a pure-lead specimen at room temperature and with a strain-rate of 10^{-2} s^{-1} : comparison between test data and model. The test consists of 25 strain-controlled tension-compression cycles over five different strain ranges (125 cycles in total). The strain ranges are: 0.25%, 0.5%, 0.75%, 1%, 1.5%. Left: experimental data. Right: curves obtained by integration of the proposed cyclic-plasticity model.

Figure 5.4 shows that the proposed model is able to reproduce the main features of pure lead under cyclic plasticity. The curvature in the transition between elastic and elasto-plastic behaviour, present at every cycle and for both tension and compression, shows a well-represented Bauschinger effect. For each strain range, the stress asymptotically trends to a 'plateau' over the whole set of 25 cycles, reproducing the cyclic hardening effects. Finally, the introduction of a strain-memory variable with a limit surface in the plastic-strain space

Chapter 5. Mechanical characterization and modelling of pure lead

enables the model to successfully replicate non-Masing behaviour: the asymptotic stress values vary with the strain range, and for each of them the stress 'plateau' matches the one obtained experimentally.

6 Conclusions

This thesis work presented the development of a new proton-driven neutron spallation target for the neutron Time-Of-Flight (n_TOF) facility at CERN, the European Laboratory for Particle Physics.

The manuscript describes the target design process from its first conception, with an analysis of different possible target concepts, to the final design, through a process of optimization aimed to maximize the physics reach as well as thermo-mechanical performance. The work required the cooperation of teams of experts in different fields of physics and engineering at CERN. The contribution of the author presented in the manuscript consists of:

- The execution of numerical studies to assess the thermal and structural response of the different target solutions examined. These studies have been performed with modern tools and software packages based on Computational Fluid Dynamics and Finite Element Method.
- The conception and construction of target prototypes; the design and execution of tests under proton-beam irradiation in dedicated facilities at CERN.
- The formulation of material constitutive models to reproduce complex effects in the behaviour of pure lead, the target core material, such as creep, cyclic hardening, Bauschinger effect, and non-Masing behaviour.
- The follow-up of the target construction and support in the phase of commissioning with beam.

The work carried out introduces novel scientific methods, applying them to the field of target design. It will serve, therefore, as a valued reference in the future for the accelerator/target community in the world.

Chapter 1 provides a description of the n_TOF neutron time-of-flight facility, which is part of the CERN complex of particle accelerators. The facility consists of a proton-driven neutron

source, based on a lead spallation target, and two neutron beamlines delivering neutrons to two experimental areas. The chapter introduces the history and the scientific relevance of the facility, placing it in the landscape of neutron source facilities in the world. A short review of the two previous targets of the facility (first and second generation) is then presented, highlighting the main issues encountered (especially erosion-corrosion), and introducing a description of the typical thermal response of this kind of devices when operating under pulsed proton-beam irradiation. The rationale for the design, production, and installation of a new target of third-generation (Target #3) is finally presented.

Chapter 2 treats in more detail the content of a manuscript published by the author in the context of the thesis work [40]. The main scientific and technological objectives to be pursued in the design of the new target are first listed and a background on the computational tools and methods exploited is provided. The chapter presents the evolution of the target design starting from a list of different conceptual ideas that are compared on the basis of physics performance and thermo-structural response (temperature values reached and mechanical stresses). The process converges towards the final target design, consisting of a series of pure lead slices cooled by nitrogen gas.

Chapter 3 includes the content of the main publication related to the thesis work [41]. It is a detailed description of the final target design, which is examined through in-depth thermo-mechanical analyses. The development of a dedicated constitutive model to estimate creep deformations during the target lifetime is described. The high stresses reached in pure lead, during the dynamic transient response of the target after a proton-pulse impact, are identified as a potential weakness of the new target design. On the other hand, the inherent uncertainty in the numerical models used in predicting the actual state of pure lead at the end of the target lifetime led to the decision to perform a beam irradiation test on a target prototype to validate the capability of the pure lead core to maintain its integrity during the operation of Target #3.

In Chapter 4, details about the prototyping activity and the execution of the tests under beam irradiation are described. A small-scale prototype of the final target concept was manufactured and tested under beam irradiation, with the objective of verifying the capability of the pure lead core to maintain its integrity when subjected to high-intensity short proton pulses. The design studies for the definition of test conditions representative of the new target operation are presented, along with the manufacturing of the test setup and the instrumentation adopted to run successfully run the test. After the test, the irradiated prototype was inspected by means of neutron tomography, confirming the soundness of the target core and the absence of defects. Hardness measurements and strain-hold tests have shown the proclivity of pure lead to stress relaxation and hardening recovery.

An additional beam irradiation test was carried out on an alternative target concept consisting of a lead cylinder with Ti-6Al-4V cladding, cooled by an active water circuit. The Ti-6Al-4V layer protects the lead core from water erosion-corrosion, but must bear the loads induced by the thermal expansion of the lead core when irradiated. This second test had the objective

of assessing the capability of the Ti-6Al-4V cladding layer to maintain its integrity under more severe beam loads, capable of melting the lead core. The design and optimization of the Ti-6Al-4V-clad lead core is described, which included the necessity of adding thick beryllium plates to the core assembly to avoid excessive deformations of the Ti-6Al-4V layer. The optimization procedure included also the addition of components to redistribute stresses in the Ti-6Al-4V cladding, while reducing tensile stresses on welds. This prototype was also inspected by means of neutron tomography after the beam irradiation test: the robustness of the Ti-6Al-4V cladding layer was validated, but the core parts in beryllium and lead revealed considerable damage, to the point of compromising the neutron production and the physics performance of this target concept. The concept may therefore be of interest for further investigation, as it may still be viable if it is subjected to lower energy density (larger beam size and/or lower intensity) or the design is further improved to limit the permanent expansion of lead inside the Ti-6Al-4V container.

In Chapter 5, an advanced constitutive material model is proposed to reproduce complex effects in pure lead when subjected to multiaxial cyclic plasticity. The results of cyclic-plasticity mechanical tests at different values of temperature and strain-rate are presented and used to identify the parameters needed to completely define the model. The results of the mechanical tests revealed a complex material response, which includes effects such as cyclic hardening, Bauschinger effect, and non-Masing behaviour. As a demonstration of the capability of the proposed model to reproduce these effects, a comparison between experimental data from one of the cyclic tests and simulated data from the proposed constitutive model is shown. The comparison shows a good match between the experimental data and the numerical results, and confirms the capability of the proposed model to reproduce all the mentioned effects.

The new third-generation target was installed in the n_TOF facility in 2021, with first beam on target in July 2021. The target commissioning lasted until November 2021, with a gradual increase in intensity until it reached nominal operating conditions and beam load (8.5×10^{12} protons per pulse and $1.67 \times 10^{12} \text{ p}^+/\text{s}$). During this period of time, the users of the facility were able to characterize the neutron beams reaching the experimental areas, confirming the physics performance simulated in Sec. 3.3. The first four months of operation validate, so far, the soundness and reliability of the target design, with a target working flawlessly as indicated by the available instrumentation: temperature, pressure, and flow sensors on the nitrogen cooling circuit lines; radiation-hard thermocouples installed in the target core; a gas-analysis system with mass spectrometry integrated in the nitrogen circuit to detect radioactive species entering the nitrogen flow during the target operation. Among the conditions in which the target operated so far, during the operating conditions closest to the simulated ones the thermocouples measured a maximum temperature of 80°C on the surface of the 2nd lead slice. This value is in line with expectations, as shown in Fig. 3.13.

6.0.1 Recommendations for further work

The constant progress in physics research drives the demand for better performing particle production targets. The choice of materials to be used in these devices is heavily constrained by physics requirements, which leads them to be subject to increasingly demanding thermo-mechanical loads. Under such conditions, target design practice requires more accurate simulations of nonlinear material behavior. In these cases, material behavior (in terms, for instance, of stress–strain relationship) continually evolves during the simulation, requiring the use of advanced constitutive models. These should ideally be coupled with increased use of multi-pulse simulations, in order to simulate the material behaviour not only during the first load cycles, but further along the evolution of its constitutive relationship. For the first time, the progress in the availability of computing power and increasingly efficient algorithms makes this type of advanced modeling possible.

The constitutive models presented in this thesis work can be further improved by more complete mathematical formulations. They can include, for example, the effects of stress relaxation and hardening recovery, in addition to the effects already included, in the same constitutive model. Other possible additions are models based on modern theories of crystal plasticity and damage laws incorporated into the constitutive model. In addition to the mathematical formulation of advanced constitutive models, further development must include the implementation of such models in numerical codes with efficient algorithms, and methods for the effective operation of such algorithms in the simulation of both *fast* events (such as the dynamic response of materials after the impact of a short beam pulse), and *slow* events (such as the material response in the time-interval between beam impacts).

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PERSONAL INFORMATION

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WORK EXPERIENCE

NOV 2016 <i>Present</i>	CERN, Geneva / EPFL, École Polytechnique Fédérale de Lausanne <i>Doctoral Student</i> • Enrolled in the EPFL doctoral programme in Mechanics, in the context of the CERN Doctoral Student Programme. • Performed studies on the thermo-mechanical behaviour and the dynamic response of the new neutron spallation target for the CERN's n_TOF facility when subjected to proton-beam impacts and extreme thermo-mechanical stress, cyclic plasticity and ratcheting phenomena. The analyses have been performed with the help of FEM (Ansys, LS-Dyna) and CFD (CFX/Fluent) codes. • Coordinated the execution of material characterization tests at high temperature and high strain-rate. • Formulated and implemented material constitutive models for FEM codes to predict high strain-rate and creep behaviour of the pure lead target. • Designed and managed the production of target prototypes and the execution of a proton-beam irradiation experiment in the CERN's HiRadMat facility. • Supervised three master's students on the execution of FEM and CFD thermo-mechanical studies. References: Marco CALVIANI · marco.calviani@cern.ch Roland LOGÉ · roland.loge@epfl.ch
APR 2016 OCT 2016	CERN, Geneva (Switzerland) <i>Mechanical Engineer</i> • Project engineer for the n_TOF Facility Consolidation Project. • Managed the R&D activities, including the design and production of several prototypes of the new n_TOF neutron spallation target (Target #3). • Coordinated, among different CERN groups and departments, the design of the neutron target. • Contributed to the target design by performing FEM (Ansys) and CFD thermo-mechanical studies on components of the new target station. Reference: Marco CALVIANI · marco.calviani@cern.ch

JAN 2015 MAR 2016	CERN, Geneva (Switzerland) <i>Technical Student</i> - Performed FEM (Ansys) thermo-mechanical studies on the dynamic response of different beam intercepting devices (especially beam dumps) when impacted by proton-beam pulses. - Drafted a technical note on the operation of the TED (Target Extraction Dump) with LIU (LHC Injector Upgrade) beam parameters, on the basis of the performed studies. Reference: Antonio PERILLO MARCONE · antonio.perillo-marccone@cern.ch
AUG 2014 DEC 2014	CERN, Geneva (Switzerland) <i>Internship</i> Performed structural and vibrational studies on a rotary stage with a compliant mechanism guiding a crystal collimator, in the context of the CERN's UA9 experiment. Reference: Alessandro MASI · alessandro.masi@cern.ch
SEP 2010 JAN 2011	Piaggio Aero Industries S.p.A., Naples (Italy) <i>Internship</i> - Contributed to the design of the tailplane of a business jet-aircraft by performing FEM (Nastran) structural (static and buckling) analyses. - Drafted a specification for the structural validation of the tailplane through a mechanical test on a prototype, evaluating the most representative test loads by means of an optimisation algorithm. Reference: Enrico ARMENTANI · enrico.armentani@unina.it
2010 2013	UniNa Corse (University of Naples Formula SAE team), Naples (Italy) <i>Mechanical Engineer, Chassis and Suspension-System Unit</i> - Contributed to the design and production of an open-wheel race car for Formula Student competition. - Performed structural optimisation studies for different components of the race car (sandwich-structured composite chassis and suspension-system parts) with the help of FE codes (Ansys, Nastran) and topological optimisation algorithms. - Contributed to establish collaborations with technical sponsors for the production of the vehicle.

EDUCATION

MECHANICAL ENGINEERING FOR DESIGN AND PRODUCTION

Master's Degree

University of Naples "Federico II" - Final Degree Mark: 110/110 Cum Laude

MECHANICAL ENGINEERING

Bachelor's Degree

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PUBLICATIONS

MAIN AUTHOR

- 2021 **Design of the third-generation lead-based neutron spallation target for the neutron time-of-flight facility at CERN**
Physical Review Accelerators and Beams, **24**, 093001
R. Esposito et al.
- 2020 **Design of the third-generation neutron spallation target for the CERN's n_TOF facility**
Journal of Neutron Research, **22**, 221
R. Esposito and M. Calviani.
- 2018 **Design, prototyping, activities and beam irradiation test for the new n_TOF neutron spallation target**
Proc. 9th Int. Particle Accelerator Conf., Vancouver
R. Esposito et al.
- 2017 **Design of the new CERN n_TOF neutron spallation target: R&D and prototyping activities**
Proc. 8th Int. Particle Accelerator Conf., Copenhagen
R. Esposito et al.

MASTER'S THESIS SUPERVISION

- 2017 **Modélisations thermomécaniques et prototypage d'une cible pour faisceau de protons**
Université de technologie de Belfort Montbéliard (UTBM), Master's Thesis
M. Bergeret (CERN, Switzerland – UTBM, France)
- 2017 **Thermomechanical simulations for the design of the n_TOF target #3**
University of Rome "La Sapienza", Master's Thesis
F. Latini (CERN, Switzerland – La Sapienza, Italy)

LANGUAGES

ITALIAN: Mother tongue
ENGLISH: Fluent spoken and written level
FRENCH: Basic spoken and written level

PROFESSIONAL SKILLS

FEA and CFD software: Ansys, LS-Dyna, Autodyn, Nastran, Fluent, CFX
Design software: CATIA and SmarTeam
Other software: Mathematica, Matlab, L^AT_EX, Simulink
Programming languages: C++, Python
Project Management: Jira, MS Project