68th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams HB2023, Geneva, Switzerland JACoW Publishing
ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP48

# LATEST ADVANCES IN TARGETRY SYSTEMS AT CERN AND EXCITING AVENUES FOR FUTURE ENDEAVORS

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## *Abstract*

CERN's accelerator complex offers a variety of target systems to meet diverse scientific objectives, encompassing different beam energies, intensities, pulse lengths, and goals. The objective of future high-intensity fixed target experiments is to further advance this field. This contribution emphasises enhanced operational target systems, which significantly boost CERN's physics pursuits. An illustrative example is the third-generation n_TOF spallation neutron target, employing a nitrogen-cooled pure lead system impacted by a 20 GeV/c proton beam. Another example focuses on recent upgrades to antiproton production targets, where a high-intensity 26 GeV/c beam collides with a thin-air-cooled iridium target. Looking ahead, there are plans for new high-power target systems. One of the goals is to discover hidden particles utilizing a 350 kW high-Z production target, while another aims to enhance kaon physics through a 100 kW low-Z target. This article provides an overview of the current target systems at CERN, detailing beam-intercepting devices and engineering aspects. Additionally, it offers a preview of upcoming facilities that are on under consideration for implementation at CERN.

## INTRODUCTION

CERN's accelerator complex provides a diverse spectrum of fixed target experiments to serve scientific objectives, encompassing different beam energies, intensities, pulse lengths, and goals. Addressing the design of target systems holistically is crucial to effectively support the physics program, ensure the reliability of its materials and mechanical system, and ensure that the best ALARA radiation protection practices are employed. Generally, beam-intercepting devices, and specifically production targets, are among the most radioactive devices at CERN.

During CERN's Long-Shutdown 2 (2018-2021), the two highest power target facilities of the Proton Synchrotron (PS) complex underwent extensive consolidation programs. The Antiproton Decelerator Target (AD-T) area and the Neutron-Time-Of-Flight (n_TOF) Target Facilities saw comprehensive upgrades to their production targets to maintain reliable and safe operation. In both cases, matching pre-LS2 physics performance was the baseline. However, a significant aspect of this initiative was to enhance mechanical system reliability and, notably, mitigate concerns regarding radiation protection. Additionally, extensive efforts were undertaken to refurbish the facilities and auxiliary services.

CERN's efforts in targetry extend beyond the consolidation of existing infrastructure. Looking ahead, plans are underway for new high-power target systems. An exciting project, the High Intensity ECN3 (HI-ECN3), is set to commence a Technical Design phase (TDR) in 2024, with implementation and operation targeted for 2030 (midway through CERN's Run 4). The project will deliver a high intensity and power beam to one of two competitive and compelling experimental candidates, which will be selected by the end of 2023 from the Physics Beyond Collider (PBC) Study Group proposals [1, 2]: The Beam Dump Facility (BDF) [3] together with the Search for the Hidden Particle Experiment (SHiP) [4], and the High-Intensity Kaon Experiments (HIKE) [5] together with the Search for Hidden And Dark Objects With the SPS (SHADOWS) [6].

This article provides an overview of some of the current target systems at CERN, detailing beam-intercepting devices and engineering aspects enhancing CERN's physics endeavours. Notably the main outcomes of LS2 consolidation works for the AD-Target and n_TOF Target facilities and possible future plans for these. Additionally, it also previews upcoming target facilities that may soon be implemented at CERN.

## n_TOF TARGET

The n_TOF facility employs about 15 % of the complex protons to carry out neutron induced capture, fission and charge-particle cross-section measurements for astrophysics and basic nuclear physics research, as well as multidisciplinary measurements in medical applications and hadron therapy [7]. During LS2, the second generation water-cooled target has been removed and replaced by a new $N_2$-cooled pure lead spallation target, optimised for both the horizontal (EAR1) and vertical (EAR2) experimental neutron beamlines [8]. A complete new cooling station has been installed at the surface, and a new mobile shielding in the target pit. The latter opened the door for a new material irradiation facility named NEAR [9, 10].

The new n_TOF spallation Target (3rd generation) moves away from past water-cooled designs by employing $N_2$ cooling gas and significantly modifies the mechanical design [8, 11]. The target core consists of six slices of pure lead ($>$ 99.99 % Pb) totalling approximately 1.5 tonnes, held in place by an aluminium EN AW-6082 T6 alloy cradle incorporating intermediate anti-creep plates. This aluminium structure serves a dual purpose: optimising $N_2$ flow distribution to efficiently cool the Pb hottest surface spots, and preventing creep of the lead blocks. The precise design

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of the gap between the lead and the aluminium plates has been thoroughly studied, considering flow induced vibrations, cooling, thermal expansion and creep deformation, and mounting requirements.

The new target core is enclosed within a welded low-cobalt 316 L stainless steel vessel with a proton beam window upstream of the same material (Fig. 1), and an Al-5083 H112 moderator pointing towards the downstream neutron beamline (EAR1). The latter have been welded to the vessel via an exploded-bonded bi-metallic transition, employing pure Al and pure Ti interlayers. A second moderator for the vertical beamline (EAR2) is mounted on top of the vessel, resting over an additional Pb block to reduce photon background. Both moderators can be used with demineralised water and borated water with 1.28 % boron content. To facilitate integration, the target assembly is placed within a stainless steel frame, allowing it to be lowered into the pit using lifting hooks. The frame serves as anchor points for the cooling pipes (for $N_2$ and water) and survey targets to measure the assembly's position in the very radioactive area. The cooling pipes run through the vertical pit (same as vertical beamline), up to the completely new cooling station.

Figure 1: n_TOF 3rd generation spallation target [12].

The design phase has been paired with extensive characterisation of the non-linear temperature-dependant kinematic hardening behaviour of pure lead. A corresponding constitutive model has then been used to estimate the response of the material, particularly its dynamic stress-strain response and low-cycle fatigue. Primary and secondary creep phenomena have also been taken into account. The lead, which operates in a cyclic-plastic regime, reaches temperatures of 135 °C upon impact of the $10^{13}$ protons at 20 GeV/c in only 7 ns. The lead will possibly experience cumulative creep in the order of tens of µm during its lifetime, particularly in the region where the 15 – 30 mm$^2$ ($1\sigma$) beam is impacting [13, 14]. Extensive computational fluid dynamics (CFD) studies have also been performed to optimise the target cooling and extract the 5.3 kW of average beam power.

The new target is set for a 10 year operation. However, advancements in physics research that demand higher average beam power and precise pulse conditions will drive the development towards a new technological concepts, potentially involving liquid lead for the 4th generation target. Synergies with other CERN projects (FCCee and Muon Collider) will enable to reach these objectives.

## ANTIPROTON PRODUCTION TARGET

The CERN antiproton production target area (AD-target) encompasses an underground facility dedicated to the supply of antiprotons to the Antiproton Decelerator facility, particularly the Extra Low ENergy Antiproton (ELENA) ring. An extensive upgrade was undertaken from 2019 to 2021 to ensure a reliable antiproton supply for future physics programs [15]. This upgrade encompassed the refurbishment of the underground target area with the installation of a complete new target and magnetic horn trolley-exchange system (Fig. 2), the installation of new radiation hard SmCo permanent focusing magnets [16], new beam instrumentation equipment, and an overall decontamination and refurbishment activity. On the surface, a trolley mock-up test bench has been used to validate new components before installation. Moreover, a completely new building allocating an upgraded nuclear-grade ventilation system and services has been constructed on top of the existing shaft connecting to the target area. New powering cubicles and a 450 kA magnetic horn test bench have also been installed in an existing auxiliary building.

Looking at the production target, anti-protons are produced by impacting a $0.5 \times 0.5$ mm$^2$ ($1\sigma$) pulse of up to $1.5 \times 10^{13}$protons at 26 GeV/c from the PS during only 0.5 µm on a high density refractory target made of Iridium (Ir). The pulse extraction, which may happen every 60 to 90 s, is synchronised with the 450 kA pulse current of the magnetic horn during 60 µm, located just downstream the target to focus the $\bar{p}$ towards the downstream momentum-selection chicane. During the pulse, the D3 mm Ir core, which is encapsulated in a D15 mm graphite matrix, reaches temperatures around 2000 °C. The heat is dissipated via the air-cooled serpentine-shaped circuit embedded in the outer Ti-6Al-4V vessel [17, 18]. The instantaneous nature of the pulse gives rise to compression-to-tensile pressure waves, potentially above the material spall limit, which has been extensively studied with beam tests [19, 20].

Future plans involve the increase of the pulse intensity from the Proton Synchrotron machine, profiting from the LIU upgrades. This will impose challenging conditions on the production target, towards unexplored regimes. In this context, it is foreseen to exchange the production target on yearly basis with other refractory based advanced design concepts. The spent equipment will undergo post-

Figure 2: AD-T trolley systems of both Production target (left) and magnetic horn (right) [21].

irradiation examinations to understand the behaviour of these challenging beam conditions and support iterative target design improvements. New horn designs and testing are also foreseen, aiming at increasing the antiproton yield towards the antiproton decelerator.

## HIGH INTENSITY ECN3

### *HIKE/SHADOWS*

The HIKE/SHADOWS proposals aim to establish a 100 kW range target complex to explore kaon beams and beam dump physics. It involves a radiation-cooled graphite target or possibly helium-gas cooled beryllium, capable of absorbing up to $2.0 \times 10^{13}$ ppp every 14.4 s. This complex will replace the existing T10 target and the TAX (Target Attenuator for eXperimental areas) system. Enhancements in shielding, spanning approximately 27 m compared to the current NA62 target system, are required.

Downstream of the production target, wobbling magnets are employed to selectively adjust the momentum of secondary hadrons before they pass through the TAX collimator-absorber. The latter will consist of a series of highly performing Cu-alloy and iron blocks, designed with various aperture configurations and the capability to serve as a beam dump depending on the operational setting. An enhanced cooling system is to be outlined; preliminary calculations suggest the feasibility of a CuCrZr absorber with stainless steel Hot-Isostatically-Pressed (HIPed) cooling pipes, resembling CERN's SPS Internal Dump (TIDVG5) technology [22]. Between the Target and TAX, beam instrumentation and other intermediate collimators will be installed. Overall, ensuring improved maintenance and handling capabilities, including full remote handling of components, is crucial to meet ALARA requirements.

In total, the shielding volume for the HIKE/SHADOWS proposal represents about 150 $\mathrm{m}^3$ of cast iron and about 600 $\mathrm{m}^3$ of concrete and marble. Special attention will be given to the possibility of reusing already activated blocks from different spent CERN facilities, aligning with CERN's sustainability goals [23].

### *BDF/SHiP*

The BDF/SHiP facility plans for a high-density production target capable of absorbing $4.0 \times 10^{13}$ protons at 400 GeV/c from the SPS primary beam, aiming to enhance the production of charmed mesons and other weakly interacting particles. To minimise background particles, a hadron absorber and a magnetic muon shield are positioned downstream of the target. Due to the expected $4.0 \times 10^{19}$ protons on target per operational year, stringent radiation protection measures are required [24, 25].

The target is housed in a helium-filled vessel for leak detection. The shielding, composed of cast iron and concrete blocks, is water-cooled and housed within a primary vacuum tank to reduce air activation and radiation accelerated corrosion. Both the target and the proximity shielding inside the tank can be remotely extracted via a trolley system. The overall shielding assembly incorporates about 180 $\mathrm{m}^3$ of cast iron and 360 $\mathrm{m}^3$ of concrete and marble, also with special effort to reuse activated blocks for sustainability.

The production target, which needs to be engineered for a lifespan of 5 to 10 years, requires for physics a core material with high density, atomic and mass number, and a short interaction length, coupled with excellent thermo-mechanical properties. In the baseline design configuration, extensively study in the comprehensive design phase, foresees TZM (0.08 % titanium, 0.05 % zirconium, molybdenum-based alloy) and pure tungsten (W) as core material. If on one side an efficient cooling is required due to the high average power on target (around 350 kW), on the other side tungsten is prone to erosion, corrosion, and embrittlement when in direct contact with water. To mitigate this, a $1 - 1.5$ mm layer of tantalum (Ta) cladding with 2.5 % tungsten is to be employed via Hot Isostatic Pressing, to surround the 250 mm diameter core materials. The core is also segmented in multiple discs for optimised cooling efficiency.

Ongoing studies are looking at other target concepts, aiming at maximising the amount of tungsten in the core, and moving the sliced concept towards a compact configuration where cooling is done on the outer diameter via an external mechanically robust shroud. Besides the obvious advantage of reduced target length (for the same number of interaction lengths), it allows integrating multiple redundancy layers to keep spallation products away from migration to the cooling circuit.

## CONCLUSION AND PROSPECTS

The next few years will see the operation of new-generation targets alongside consolidated infrastructure at the n_TOF and AD-T facilities at CERN. Extensive design studies, material characterisations, computational modelling, and benchmarking through beam tests have been conducted to guarantee their operational reliability. Moreover, new ideas for future upgrades are now beginning to be explored.

Studies for a new high-power fixed target facility for either kaon physics or hidden sector searches at CERN will ramp up, with the aim of implementing it by the end of the decade.

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