A HELIUM-COOLED TARGET DESIGN AT THE SPS BEAM DUMP FACILITY (BDF) AT CERN

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Abstract

CERN's upcoming SPS Beam Dump Facility (BDF), in the framework of the HI-ECN3 project, will host the Search for Hidden Particles (SHiP) experiment to search for physics beyond the standard model. At the core of BDF is a solid, high-Z target designed to safely absorb the 400 GeV/c proton beam and dissipate an average deposited thermal power of 305 kW, while providing secondary particles for SHiP. A helium-cooled tungsten (W) design is being developed as an alternative to the initial design based on water-cooled tantalum-tungsten clad molybdenum alloy and W blocks. The new design improves the physics potential performance while simplifying the operation and maintenance of the annex systems. To validate the new concept, two static helium-filled prototype targets were tested with slow extracted beam in CERN's TCC2 North Area in 2025. In addition to the details of the helium-cooled design, this contribution outlines the prototype design and manufacture and compares online measurements with calculations, highlighting their relevance to the material testing campaign and final target design. The 2025 tests are complemented with a second beam test campaign ongoing in 2026, employing a new prototype with an active helium cooling system, to further validate the target and cooling system.

INTRODUCTION

CERN's SPS Beam Dump Facility (BDF) [1,2] will host a solid, high-Z, production target for the Search for Hidden Particles (SHiP) experiment [3,4]. A helium-cooled tungsten (W) design is being developed as the leading design [5]. Two identical, static helium-filled prototype targets, comprising W and Tantalum (Ta)-Clad W core blocks, were tested with slow extracted beam in the TCC2 target area of CERN's North Area in 2025 and are currently undergoing Post Irradiation Examination (PIE). Another prototype target employs an active helium system which directly cools identical blocks. To date, it has accumulated 1798 shots on target and is foreseen to undergo an additional ≈1200 shots during 2026.

HELIUM-COOLED TUNGSTEN TARGET CONCEPT

The helium-cooled production target is comprised of 1.5 m total of 250 mm diameter W blocks with a downstream 314 mm diameter block, see Fig. 1. The 400 GeV/c beam is slow-extracted from the SPS and swept four times during the 1 s long-spill on the target in a 50 mm radius circle to alleviate the maximum temperatures and stresses, see Fig. 2.

The 4×10^{13} POT intensity spill is followed by 6.2 s of cooldown [5], resulting in an average thermal power of 305 kW. The W blocks are separated by 4 mm thick cooling channels with forced helium convection for efficient heat removal. The number and position of channels have been optimised and concentrated near the front of the target, corresponding to the beam shower region, to keep peak stresses to 85 MPa, well below rolled W's yield strength of 300 MPa at 1.3 dpa [6,7], and surface temperatures to 307 °C, well below 400 °C where oxidation is observed to markedly increase in an oxygenated atmosphere [8–10]. The 400 g/s flow at 16 bar(abs) is 30 °C at the inlet and 180 °C at the outlet, resulting in a maximum Mach number of 0.12. The helium is distributed through a manifold support made of Inconel 625, selected to withstand the high stresses caused by large temperature gradients. The core blocks and support are encased in a stainless steel and Inconel 625 pressure vessel. The larger diameter downstream block reduces the direct shine-path from the manifold spaces and manufacturing tolerance gaps, foreseen to reduce the corresponding muon background to SHiP [11].

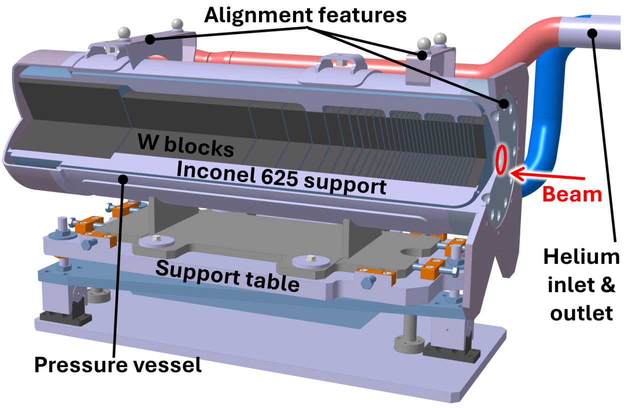

Figure 1: 3D-split view of the helium-cooled W target for the SPS BDF facility at CERN. The target core comprises 1.5 m of pure W blocks.

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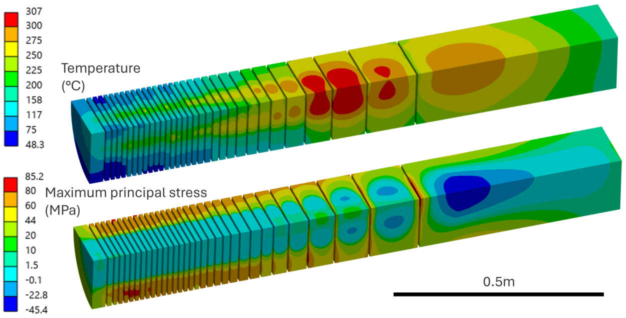

Figure 2: Beam induced temperatures and stresses of the target design. Core blocks 1–32 shown.

The peak radiation damage in the W and vessel window are expected to be 0.84 dpa and 0.1 dpa respectively, after a target lifetime of 2 × 10^{20} POT, corresponding to 5 years of operation. The upstream blocks are single hot-rolled sheets of W, while the downstream blocks 25 to 33 are W sheets joined by HIP to produce stacks of the required length. HIP blocks are selected over sintered W due to expected improvements in material properties [5, 6, 12–14]. Three Ta cladding options are being investigated for the helium-cooled target: (i) fully cladded, (ii) uncladded, and (iii) partially cladded [5]. Previous work considered Niobium cladding due to concerns of a Loss of Coolant Accident (LOCA) [15–17]. A material testing campaign is ongoing into whether further precautions are needed on the target cladding or planned helium purity level of 1 appm.

PROTOTYPE TARGET TESTING CAMPAIGN

Static Helium Prototype

The static helium prototype design comprises blocks of 5 mm hot rolled W sheets, joined by HIP with 50 µm Ta interfoils [5]. The core blocks include the 3 cladding types (i), (ii) and (iii) previously described. The blocks are separated by 304L stainless-steel spacers with 4 mm gaps between the blocks providing cooling via natural convection, Fig. 3. The core stack resides inside a steel cylinder with a concentric, flowing water-jacket. Blocks 2 to 5 were instrumented with 1 thermocouple each, within holes created by die-sinking Electrode Discharge Machining (EDM), located at the centre of the blocks with block 3 radially offset by 5 mm. The thermocouples were attached at the tip with a ceramic adhesive.

Two target heads are employed, See Fig 4. The targets were designed to produce peak stresses in Target 1 of 150 MPa equivalent to the UTS of rolled W irradiated at 1.3 dpa with a safety factor of 2 [7], and surface temperatures of 350 °C. Target 2 aimed for much higher peak stresses of ≈300 MPa and surface temperatures of ≈650 °C under beam pulses. The corresponding beam parameters are beam sigma 1 mm with 1.5 × 10^{12} p/spill and 3.5 × 10^{12} p/spill for Targets 1 and 2 respectively.

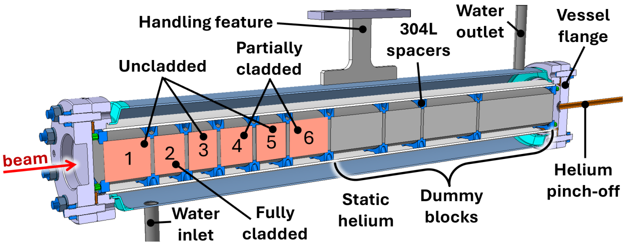

Figure 3: Static helium prototype design. The blocks comprise W-W stacks with Ta interfoils, joined by HIP. Several Ta cladding types were tested.

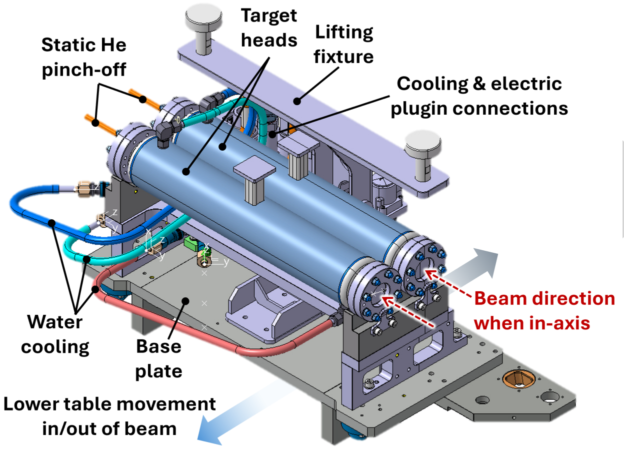

Figure 4: Assembly of the static helium prototype, comprising two target heads. The two targets were subjected to different beam intensities, allowing the core blocks to be tested at a wide range of temperatures and stresses.

Between September and October 2025 the natural-convection cooled prototype heads received 17 and 38 beam pulses respectively. The thermocouple acquisition rate of 2 Hz is likely to have missed capturing the peaks from the 1 s beam pulse. The peak thermocouple temperatures and cooldown rates are expected to be influenced by the imperfect thermocouple contact, insulation within the thermocouple, thermocouple hole depth variation and geometrical offsets from target dimensional tolerances. Further modelling of the thermocouple geometry is ongoing to investigate the relative contribution from these effects. Unexpectedly, the temperature rise in block 4 of Target 1 (TC3) reported higher than expected, which is currently under investigation, Fig. 5.

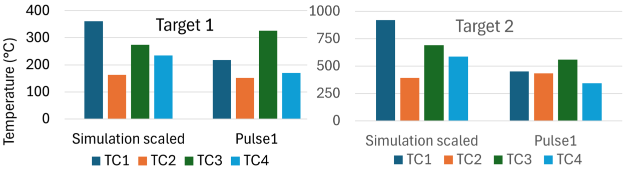

Figure 5: Simulated maximum W temperatures, scaled for measured beam intensity and sigmas, compared to measured thermocouple results. TC1 corresponds to block 2.

After the beam tests were completed, the static helium prototypes were disassembled at CERN. Two remotely controlled robots were employed to allow disassembly and examination of the targets without an extensive cool-down period and in line with ALARA principles, see Fig. 6.

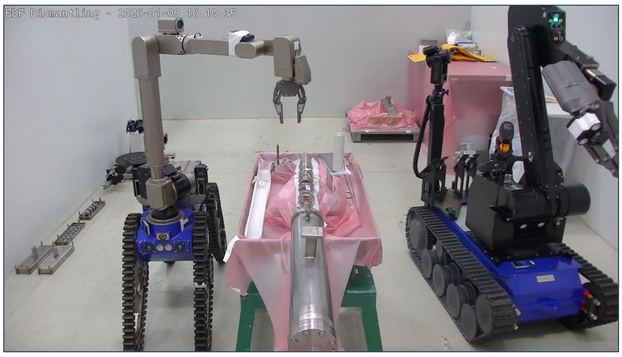

Figure 6: Static helium prototype disassembly in radiation controlled environment at CERN.

During disassembly, the core blocks were visually inspected by high-definition digital imaging and measured with a 3D laser scanner. Subsequently, the blocks were ultrasonically tested, and all measurements were compared to equivalent processes performed on the blocks prior to the target irradiation. No changes to date have been observed on any of the blocks from the target head subjected to 150 MPa stresses (Target 1). However, in Target 2, some changes have been observed in the the four blocks subjected to highest temperatures and stresses. The metrology-scan results reveal a small protuberance several micrometers in height, on the flat external surfaces in the axial-centre of 3 blocks, which were visible during disassembly. Furthermore, ultrasonic scans reveal discontinuities 12 mm in diameter within several blocks at the axial-centre, see Fig. 7. These occurred both within the W plate and at the W-Ta interface. The depths of the discontinuities often occurred within 1 mm from the thermocouple hole.

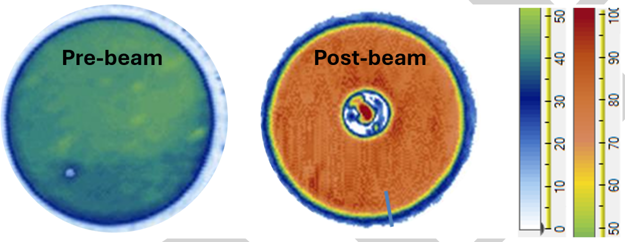

Figure 7: Ultrasonic assessment of block 2 of Target 2 (fully cladded). The ultrasonic measurements taken before and after beam impacts shows discontinuities in several blocks, only after beam tests, in the target tested at elevated temperatures and stresses. The scale is maximum amplitude of response over a given signal response window. The difference of base colour between the before and after is not significant.

Further PIE is planned including sectioning and detailed microscopy of the irradiated blocks to investigate further the nature of the discontinuities and health of the joined material.

Active Helium Convection Prototype

An additional prototype has been designed and built with an identical configuration of core blocks to the static helium prototype, with the addition of a 7th block which is completely clad with 1.5 mm pure Nb. See Fig. 8.

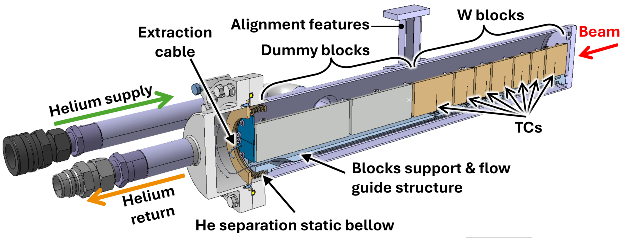

Figure 8: 3D view of prototype with active helium cooling.

The prototype utilises a completely new helium system to cool the target by forced convection at a rate of 11.6 g/s at a pressure of 14 bar(abs). The direct cooling permits a significantly faster repetition rate allowing an expected total of 3×10^3 pulses on target, corresponding to 6×10^{15} POT to test the prototype core material at low cycle fatigue. A helium system was constructed and commissioned in CERN's North Area in early 2026, consisting of a 15 kW oil-free piston compressor, filter downstream of the target, and heat exchangers downstream of the compressor and filter. The circuit was envisaged to test the helium circuit concept and to date has seen several months of consistent running. By the end of April 2026, the forced helium prototype has seen 1798 shots on target over 10 hours of dedicated beam time, with further beam time planned in the first half of 2026.

Measurements have been taken with a Laser Doppler Vibrometer to compare vibrations caused by the high velocity flow to calculations, in order to validate models to be used for the final target. During and after beam tests, mass spectrometry is performed on the helium coolant, with samples taken directly after beam tests for gamma spectrometry. To date, the gamma spectroscopy has detected Iodine and Xenon isotopes ^{123}I and ^{125}Xe. These will be used, in conjunction with sampling of the filter and heat exchanger downstream of the prototype, where contaminants are expected to coalesce, to assess whether particles or volatile contaminants migrate from the target.

CONCLUSION

The core of the production target will be constructed from hot-rolled sheets of pure W for superior material properties, consisting of a mixture of single sheets and W-W blocks joined by HIP. R&D is ongoing into the need or otherwise of exterior cladding and into the material limits of the sheets and joined blocks. A static helium-cooled prototype from 2025 is currently undergoing PIE to validate the material limits and behaviour in beam. A forced convection prototype is undergoing testing in a high-power beam, with PIE expected to begin in late 2026, to further validate the helium-cooled design.

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