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CERN BDF PROTOTYPE TARGET OPERATION, REMOVAL AND AUTOPSY STEPS

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Abstract

The Beam Dump Facility (BDF), currently in the study phase, is a proposed general-purpose fixed target facility at CERN. Initially will host the Search for Hidden Particles (SHiP) experiment, intended to investigate the origin of dark matter and other weakly interacting particles. The BDF particle production target is located at the core of the facility and is employed to fully absorb the high intensity (400 GeV/c) Super Proton Synchrotron (SPS) beam. To validate the design of the production target, a downscaled prototype was tested with beam at CERN in 2018 in the North Area primary area in a dedicated test at 35 kW average beam power. This contribution details the BDF prototype target operation, fully remote removal intervention and foreseen post-irradiation examination plans.

INTRODUCTION

The Beam Dump Facility (BDF) [1], currently in its study phase, is a general-purpose fixed target facility at CERN. In the initial phase, the facility is aimed at the SHiP experiment [2], which purpose is to investigate the origin of dark matter and other lightly interacting particles. At the core of the installation resides the target/dump assembly, whose aim is to fully absorb the high intensity SPS beam and produce amongst other particles, charmed mesons. In addition to thermo-mechanical loads, the most challenging aspects of the proposed dump lie in very high energy and power density deposition that are reached during operation, which require efficient cooling [1, 3].

The target, engineered to absorb 4×10^{13} protons(p^+)/pulse at 400 GeV/c, totalling 2×10^{20} p^+ throughout 5 years of operation, is foreseen to use a hybrid configuration composed of TZM (a molybdenum alloy with titanium and zirconium) and pure tungsten (W) materials cladded with a thin tantalum-2.5tungsten (Ta2.5W) layer (eighteen round blocks with a diameter of 250 mm and variable thickness, with a total target length around 150 cm). For the first part of the target, TZM is chosen as it is stronger than pure molybdenum and possesses a higher recrystallization temperature and better creep resistance. It is especially suited for high-temperature applications, involving demanding mechanical loads. Pure W is on the contrary selected for the second half of the target due to its known superior performance under irradiation. Both TZM and W fulfil the physics requirements, which gives preference to high Z materials. Since the target is going to be actively cooled with water to evacuate 300 kW of average power on target, a Ta2.5W cladding is foreseen all around the blocks to avoid erosion-corrosion effects as well as hydrogen embrittlement. Good thermal and mechanical bonding between core-cladding materials is achieved via hot isostatic pressing (HIP) [4].

PROTOTYPE TARGET

In order to validate the design, material selection, manufacturing of the target's core blocks and thermo-mechanical calculations, a reduced scale prototype was built with core blocks of 80 mm diameter, and lengths and materials identical to the final device. Out of the eighteen blocks, four of the most representative in terms of temperatures and thermally induced stresses were instrumented with strain gauges and temperature sensors (see Fig. 1) to allow live monitoring during the beam tests and later comparison with the FEA (Finite Element Analysis) calculations.

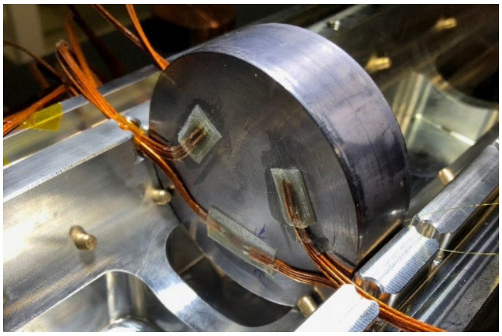

Figure 1: BDF target prototype instrumentation.

The set of target blocks of the prototype is entrenched in two half-shell parts which allows free expansion in the axial direction while guiding the 20-bar cooling water in a serpentine-like circuit around the blocks.

The shells assembly is inserted into a cylindrical stainless-steel tank guaranteeing the water leak tightness. The water inlet which connects straight into the shells assembly as well as the outlet which collects the return water filling the tank are located on the upstream side of the tank. Downstream, a flange provides the instrumentation connections and a draining port. The tank is finally mounted on a collimator-like plug-in table, which altogether allow a fully remote handling of the prototype target (see Fig. 2). The prototype is designed to be the first complete remotely dismountable device of its type at CERN.

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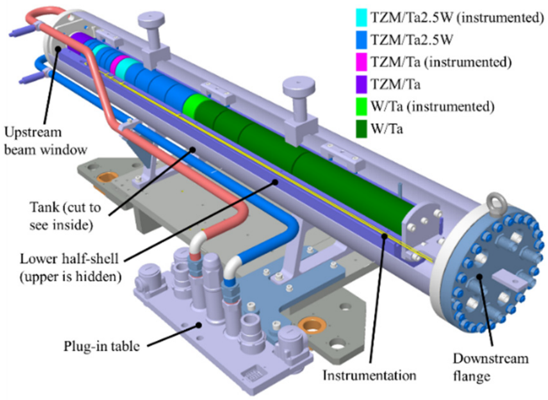

Figure 2: BDF target prototype main components.

BEAM TESTS

The BDF prototype target was irradiated during the autumn of 2018 upstream the T6 target, located in the TCC2 primary zone of the North Area at CERN [5].

A total of 2.4 × 10^{16} protons on target have been extracted from the 400 GeV/c SPS beam. With intensities between 3-4 × 10^{12} p^+/cycle (7.2 s cycle with 1s of beam extraction), the obtained average beam power was between 27 and 35 kW, representing 18-23 kW of heat deposition in the cladding and core materials. The reduced intensity with respect to the final target (4 × 10^{13} p^+/cycle) was balanced by the absence of beam dilution (four circular sweeps during the 1s extraction for the final target). This beam setup permitted having identical energy densities and reproducing the same level of temperatures and thermally induced stresses on the prototype as on the final target (with 4 × 10^{13} p+/cycle, the expected maximum von Mises stress is of 95 MPa and maximum temperatures of 160 °C on Ta2.5W, 180 °C and 150 °C on TZM and W respectively). The most critical measurements of the tests (with Pt100 and strain gauges (SG)) revealed good agreement with the FEA calculations [6], as summarized in Table 1.

Table 1: Maximum[1] Temperatures, Strains Measured (Transverse & Radial) and Equivalent Stress Amplitudes vs Calculated via FEA for 3.75 × 1012 p+/cycle

Cladding Material (block)	**T_{Pt100} [°C]**	**T_{FEA} [°C]**
Ta2.5W(4)	38.8±0.5	40
Ta(8)	46±0.5	43.8

	$\Delta\varepsilon_{SG}$ [µm/m]	**$\sigma_{a,SG}$ [MPa]**	**$\Delta\varepsilon_{FEA}$ [µm/m]**	**$\sigma_{a,FEA}$ [MPa]**
Ta2.5W(4)	190 |-450	43	170 | 390	37
Ta(8)	100 |-230	22	87 |-250	23

REMOVAL INTERVENTION

With the purpose of later characterizing and understanding the survivability of the highly activated target blocks through a post irradiation examination (PIE) campaign, an entirely remote intervention took place in January 2020 to extract the blocks. The intervention comprised the removal and opening of the prototype target, extraction of target blocks and storage of the radioactive device. At this stage, the cooling circuit had already been flushed to minimize water contamination during the intervention.

CERN's Teodor® and CERNBot robots [7], together with the overhead crane in TCC2 were used in the final intervention, after substantial mock-up testing and validation.

Target Removal

Preceded by the opening of the shielding over T6, the plug-in system was unscrewed with Teodor and the prototype taken to a bunker for further dismantling (see Fig. 3).

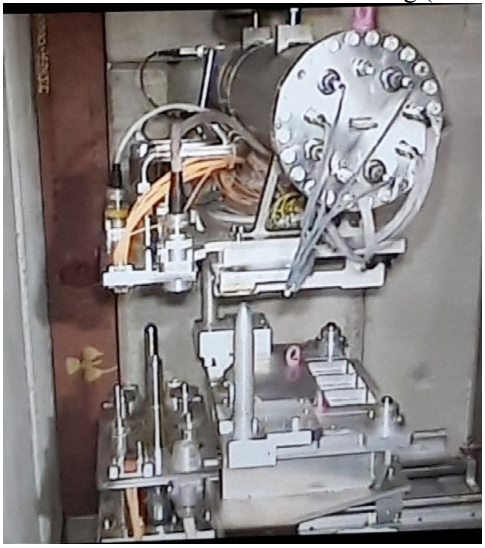

Figure 3: Unplug-in of the BDF target prototype from T6 table.

At the bunker, all the cabling connectors on the downstream flange were detached using the clamp of Teodor (see Fig. 4) and the remaining stagnant water in the tank was drained.

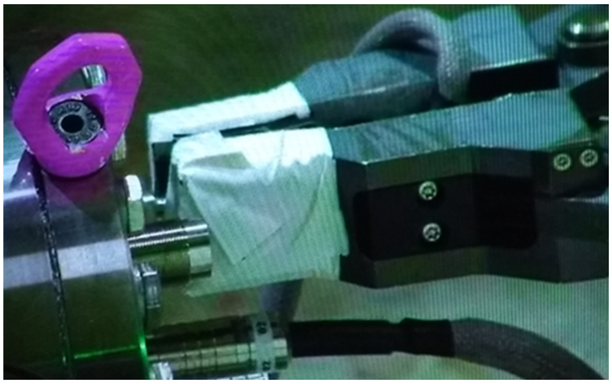

Figure 4: Cabling disconnection.

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[1] Maximum within all the measured values by the instrumentation. The FEA values are at the same location of the PT100 and SG. The actual maximum temperatures in the blocks are higher but were not directly measured: expected (via FEA) max stress amplitude (σ_a) of 50 MPa (105 MPa von Mises equivalent) and max temperature of 250 °C on the Ta2.5W

Core Opening

The tank was opened by first unscrewing the upstream, bolts which were holding the half-shells core, followed by the disconnection of the downstream flange. A joint operation between the two robots and the overhead crane allowed pulling out the downstream flange, cutting the instrumentation wires and extracting the half-shells core from the inside of the tank (see Fig. 5).

The upper shell was then unscrewed using CERNBot and removed with the overhead crane, allowing a first glimpse on the irradiated target blocks.

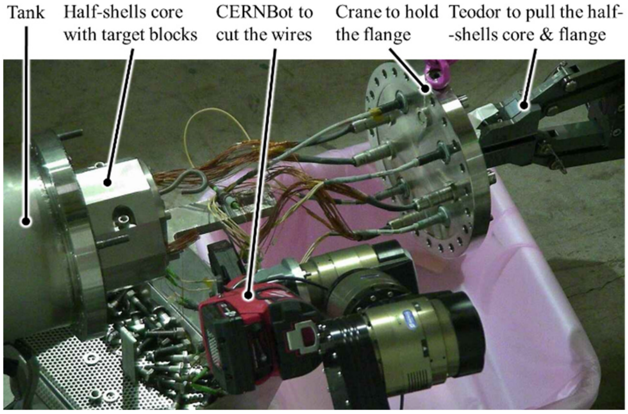

Figure 5: Remote wire cutting.

Target Blocks Extraction

Before extraction, a radiation dose measurement and a wipe test for contamination measurements were performed, and all the blocks were marked with a pen to identify their angular orientation with respect to the beam. The measured dose rates on contact with the target blocks were as high as 90 mSv/h (after 1.5 years cool-down): clear justification for a design thought for fully remote handling and dismantling with the robotic capabilities of CERN.

Two batches of six target blocks were extracted with Teodor equipped with a vacuum clamp tool (see Fig. 6) and placed in two boxes. One of each, containing the most relevant blocks, is stored in a dedicated shielded container for later post irradiation examination of the target blocks.

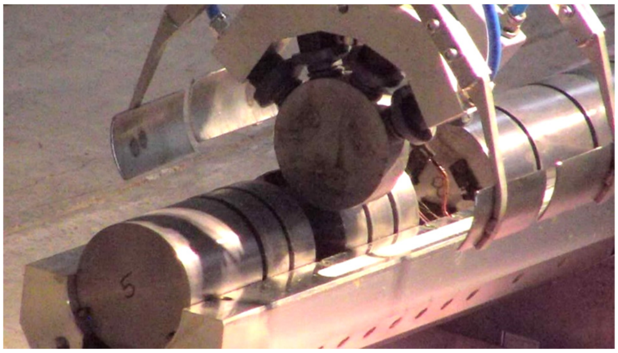

Figure 6: Target block extraction with vacuum clamp.

POST IRRADIATION EXAMINATION (PIE) PLANS

A PIE is currently on going with the purpose of characterizing six target blocks (four of which instrumented during the beam tests), particularly the cladding surface, core-cladding interface, cladding and core bulk materials. The activity consists of the following steps:

- Film dosimetry: to assess the real beam position during the tests.
- Optical microscopy to assess the presence of any visible beam-induced damage on the blocks (see Fig. 7).
- Energy-dispersive X-ray spectroscopy (EDS) of the target blocks flat surfaces to measure their elemental and chemical composition.
- Metrology of the blocks. For instance the measurement of the diameter and length of the blocks, profilometry and roughness measurements on the flat surfaces to assess any surface modification or swelling.
- Ultrasonic testing of the cladding-core interface to analyse in a non-destructive manner the integrity of the cladding-core interface.
- Microstructural characterization of the bulk core and cladding materials and their interface. Optical microscopy (OM), scanning electron microscopy (SEM), EDS and characterization via Electron backscatter diffraction (EBSD) will be employed.
- Hardness measurement of the bulk core and cladding materials at various radial and axial distances from the beam axis.
- Mechanical tensile characterization of the bulk core materials.
- Mechanical shear test of the cladding-core interface.

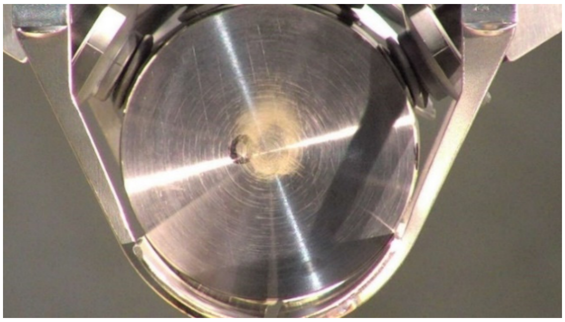

Figure 7: Visual inspection upon removal intervention revealed surface coloration around the beam impacted area.

CONCLUSION

Following the design of the BDF Target, a fully remote handling prototype has been built and irradiated at CERN. The beam test conditions replicated the temperatures and stresses of the final device, and good agreement was found between the measurements and the FEA calculations. In order to analyse the state of the highly radioactive target blocks, their removal took place in a successful fully remote intervention. A detailed post irradiation examination is ongoing to characterize and understand the survivability of the target materials.

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