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BEAM DUMP FACILITY TARGET: DESIGN STATUS AND BEAM TESTS IN 2018

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Abstract

The Beam Dump Facility (BDF) Project, currently in its design phase, is a proposed general-purpose fixed target facility at CERN, dedicated to the Search for Hidden Particles (SHiP) experiment in its initial phase.

At the core of the installation resides the target/dump assembly, whose aim is to fully absorb the high intensity 400 GeV/c Super Proton Synchrotron (SPS) beam and produce charmed mesons. In addition to high thermo-mechanical loads, the most challenging aspects of the proposed installation lie in the high energy and power density deposition that are reached during operation.

In order to validate the design of the BDF target, a scaled prototype is going to be tested during 2018 in the North Area at CERN, upstream the existing beryllium primary targets. The prototype testing under representative beam scenarios will allow having an insight of the material response in an unprecedented regime. Online monitoring and an extensive Post Irradiation Experimental (PIE) campaign are foreseen.

The current contribution will detail the design of the BDF target/dump core as well as the design and construction of the prototype target assembly.

THE BEAM DUMP FACILITY TARGET

The Beam Dump Facility (BDF) [1], currently in its design phase, is a fixed-target facility proposed to be situated at the North Area of the SPS. This general purpose facility is aimed at the Search for Hidden Particles (SHiP) experiment [2] in the first instance. The BDF target sits at the core of the installation with a double function: on one side, it must absorb safely and reliably the full SPS primary beam. On the other side, its design has been optimized from a physics perspective point of view (in terms of geometry, material, gaps, etc.) to maximize the production of charmed mesons. It can be considered as a beam dump/absorber, since it will contain most of the cascade generated by the interaction with the primary beam. The high power deposited is one of the main challenges of the BDF target design, with 320 kW of average power deposited and 2.56 MW over the 1-second slowly extracted spill.

Such high beam power expected on target requires beam dilution [3], as well as a large beam spot diameter, in order to avoid target failure. The dilution pattern generated by the upstream magnets and the beam size have been optimized taking into account the aperture restrictions from the extraction line magnets and the mechanical performance of the target. As a result, the SPS primary beam will be diluted in 4 turns over a 50 mm radius circle for each 1-second pulse, with a beam spot size of 8 mm 1σ.

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Target Design and Material Selection

The materials sought for the BDF final target are high-Z materials with a short nuclear interaction length, in order to increase the re-absorption of pions and kaons produced in the intra-nuclear cascade process. The proposed target design currently consists of several collinear cylinders of TZM ((0.08%)titanium-(0.05%)zirconium-molybdenum alloy) and pure tungsten (W), cladded with pure Ta or a W-containing Ta-alloy, with a diameter of 250 mm and different thicknesses, for a total effective target length of around 1.3 m (see Figure 1). For the first part of the target core, TZM is chosen because of its higher strength, better creep resistance and higher recrystallization temperature compared to pure molybdenum [4]. For the second part of the target, pure W is selected, since it fulfills the physics requirements (high density and short interaction length) and has proven a good performance under irradiation [5]. The proposed target cylinders have variable lengths, which have been iteratively adjusted to have the most uniform possible energy deposition in each of the blocks. The optimization of the blocks' length aims at minimizing the level of temperatures and stresses reached in the target materials.

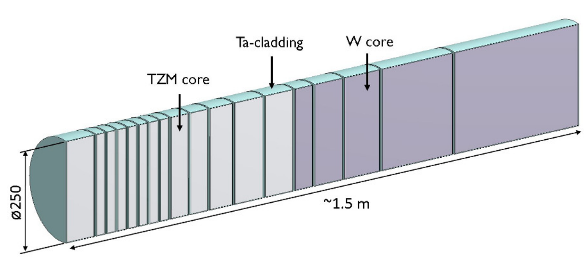

Figure 1: Layout of the Beam Dump Facility target core.

Given the high energy deposited and the high temperatures reached during operation (above 180°C in the cladding and core materials of several target blocks after the beam impact), the target requires active water cooling. The cooling water will flow through a 5 mm gap foreseen between the different blocks with high (roughly 4 m/s) velocity, in order to provide an effective heat transfer coefficient (HTC) between the cooling medium and the blocks. However, the

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high-speed water in contact with the pure W and TZM blocks could induce undesired corrosion-erosion effects. Therefore, all the target core blocks will be cladded via diffusion bonding achieved by means of Hot Isostatic Pressing (HIP) with Ta or Ta-alloy [6] [7], due to their high corrosion resistance, and its convenience as high-Z material with short interaction length.

The preliminary structural calculations performed on the BDF final target assuming pure Ta as cladding material led to the conclusion that the maximum stresses expected in the tantalum cladding may be critical for the target operation. The simulations performed have shown that the Tantalum cladding of some of the target blocks can reach a maximum Von Mises stress of 110 MPa, leading to an unacceptable safety margin with respect to the yield strength of tantalum at high temperatures, which is assumed to be around 100 MPa at 150°C [8].

Plastic deformation of the cladding material is an undesired effect, taking into account that the core materials are expected to work always in the elastic regime. The cyclic plastic deformation of the cladding during a long period could lead to premature fracture of the tantalum layer, and/or to detachment of the cladding with respect to the base refractory metal, reducing or blocking the heat dissipation through the cladding material.

A tantalum-tungsten alloy with 2.5% content in pure W (Ta2.5W) has been considered as alternative cladding material, this alloy having a much higher strength at high temperatures than pure Ta [9]. Ta2.5W has similar thermo-physical properties to pure Ta, a good corrosion-erosion resistance as well, and is expected to present the same diffusion bonding compatibility with W and TZM as pure Ta.

BDF TARGET PROTOTYPE

Due to the unprecedented conditions to which the BDF target materials will be exposed in terms of temperature, stress and radiation levels, it has been proposed to test a prototype of the BDF target under proton beam. A dedicated experiment will be executed in the CERN North Area Primary Target zone during 2018 [10], in particular upstream the existing T6 beryllium target. The unknown reliability of the intermetallic bonded surfaces when exposed to the beam impact is one of the main motivations for this test. The prototype core is foreseen to be impacted by 10^4 pulses, and it has been designed to achieve a meaningful reproduction of the level of temperatures and stresses reached in the BDF final target [11].

Target Prototype Operation

The target prototype will be tested in the CERN's North Area under a non-diluted primary proton beam but using the same cycle configuration as of the BDF final target (i.e. spill length of 1 second and repetition rate of 7.2 seconds). Consequently, the required beam intensity to reach representative temperatures and stresses with respect to the final target is lower and expected to be in the range of $3\text{-}4{\cdot}10^{12}$ p+/cycle. Table 1 shows a comparison between the BDF final target beam and the target prototype beam parameters.

The experimental setup foreseen in the North Area for the prototype testing is justified by the need of a slow extracted beam to reproduce the final BDF target operational conditions, which could not be achieved under the fast extracted beam of other dedicated experimental facilities at CERN such as HiRadMat [12]. The prototype assembly has been installed on a motorized table with horizontal translation motion which will align the target replica with the beam axis during the dedicated beam time for the test, and will remove it from the beam trajectory during normal SPS operation.

Table 1: BDF Final Target and Target Replica Beam Parameters Comparison

Baseline characteristics	BDF final target	Target prototype
Proton Momentum [GeV/c]	400	400
Beam intensity [p+/cycle]	$4{\cdot}10^{13}$	$3\text{-}4{\cdot}10^{12}$
Beam dilution	4 circular sweeps/s	No
Expected r.m.s spot size (H/V) [mm]	8/8	3/3
Cycle length [s]	7.2	7.2
Spill duration [s]	1	1
Average beam power on target [kW]	320	20
Average beam power during spill [MW]	2.5	0.14

Target Prototype Design and Construction

The target replica consists on a reduced scale prototype composed of 80 mm diameter cylinders and the same thickness distribution as the BDF final target, as shown in Figure 2. Tantalum and Ta2.5W are used as cladding materials in order to evaluate the performance of both materials during operation. The prototype assembly includes two concentric stainless steel tanks: the outer tank ensures the leak-tightness of the assembly, compatible with an operational pressure of 22 bar, provides an interface for the electrical and water connections, and encloses the inner stainless steel tank. The target blocks are sitting on the inner tank lower shell, only constrained in the Z-direction by 2 pins that allow free-body expansion of the blocks within 50 µm, but ensure a gap of 5 mm between the blocks, necessary for the water cooling.

The target prototype cooling system design intends to replicate the most critical characteristics of the cooling system foreseen for the final BDF target: high pressure, 5 mm channels and high water speed between the target blocks to achieve a significant heat transfer coefficient. Several flow configurations have been investigated to minimize the required mass flow rate and at the same time obtain uniform fluid velocity and high HTC in the channels. For the

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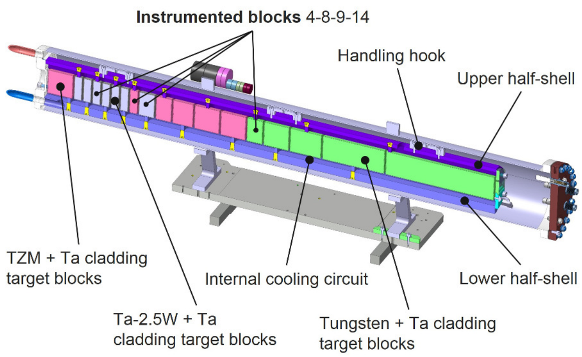

Figure 2: BDF target prototype assembly layout.

specific set of parameters of the target prototype in T6, the single-channel (serpentine) configuration presented in Figure 3 results to be the optimal one in terms of flow velocity uniformity and overall mass flow rate. The cooling circuit design carried out for the target replica made possible to identify the main challenges and potential solutions for the future design of the BDF target cooling system.

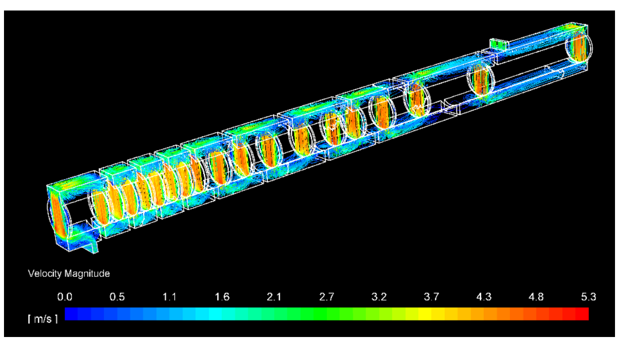

Figure 3: Velocity pathlines from a 3D CFD simulation of the target replica cooling circuit.

The thermal calculations results show that, due to a combination of low thermal conductivity, high power deposition and potential localized boiling, the cladding temperature is a critical parameter. In order to reproduce the temperature level reached in the final BDF target blocks while limiting the cladding temperature, a surface heat transfer coefficient of about 16000 W/m^2K has been selected by setting the average flow velocity at 4 m/s [11]. In reality, the actual value of HTC predicted by the simulations is slightly higher and highly non-uniform. The calculation assumptions are therefore likely to be conservative.

According to the structural simulations carried out, the thermal stress in the prototype target blocks will lead to a reasonable approximation of the state of stresses in the BDF final target. Several target blocks will be instrumented with both temperature and strain gauges, as well as with fiber Bragg grating (FBG) optical fibers, with the purpose of crosschecking the thermal and structural calculations [13]. The instrumentation of the target cylinders under a high pressure and high velocity water flow, added to the high radiation levels to which the gauges will be exposed (of the order of 10 MGy), has been identified as one of the most challenging aspects of the prototype test preparation.

The target replica assembly has been designed to provide full compatibility with the available remote handling systems, given the high radiation level expected in the target replica after 10^4 pulses (in the order of Sv/h at contact) [14]. The water and electrical connections have been integrated in a radiation-hard interface that allows the target to be connected and disconnected remotely. The layout of the target tank, support, motorized table and connection assembly is shown Figure 4.

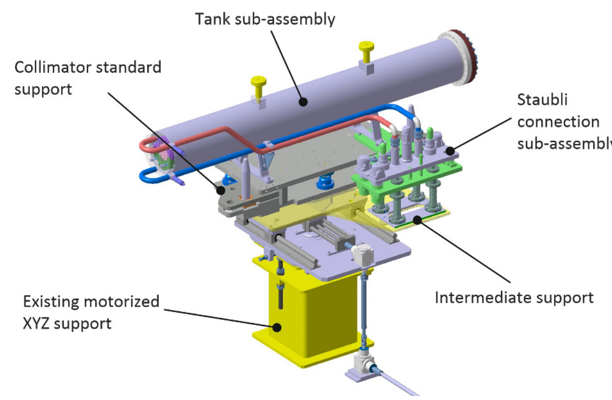

Figure 4: BDF target prototype supporting structure and interfaces assembly.

A Post Irradiation Examination (PIE) campaign is foreseen in order to characterize beam-induced property changes in the target materials, as well as to evaluate the bonding contact between the tantalum cladding and the core cylinders. The target assembly opening and the blocks extraction for PIE will be performed remotely, and will take place at least 6 months after the beam test, so as to reduce the radiation dose to acceptable limits.

CONCLUSIONS

The BDF target design is one of the key aspects in the comprehensive study of the proposed Beam Dump Facility at CERN. This target will be subjected to unique conditions during operation, leading to a complex material selection process and mechanical design.

The studies performed for the target prototype design have set a starting point for the design of the final BDF target by identifying the main challenges of the target design (cooling system, installation, remote handling, etc.).

Additionally, the outcome of the beam tests in 2018 will validate the results of the thermo-mechanical simulations performed, and the future PIE will certainly lead to a better understanding of the behaviour of the target materials under irradiation and at high temperatures, simplifying the material selection for the final BDF target.

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