I. INTRODUCTION

Currently in its design phase, the new Beam Dump Facility (BDF) is a multi-purpose facility aiming for high-intensity beam dump and fixed target experiments. The first objective of the facility is to explore Hidden Sector models and to search for Light Dark Matter with the Search for Hidden Particles (SHiP) experiment [1–4]. The new facility also offers the opportunity to explore rare $\tau$ lepton decays and $\tau$ neutrino studies through fixed target flavour physics programs.

At the core of the facility, a dense target/dump surrounded by heavy shielding will have a double function: (i) to absorb safely and reliably the entire energy of the 400 GeV/c Super Proton Synchrotron (SPS) beam; (ii) its design must be optimized from a physics perspective in order to maximize the production of charm and beauty hadron decays, and photons, all of which are potential sources of very weakly coupled particles. A series of particle detectors will be situated downstream of the target complex, with the aim of searching for portal interactions with hidden sector particles, including Dark Matter candidates.

The BDF target can be considered as a target/dump assembly, since it will contain most of the particle cascade produced by the primary SPS beam interaction. This requirement leads to a very challenging target design, given the high energy and power density that will be deposited during operation, and the subsequent thermal and structural loads. The materials sought for the production target are high-A/Z materials with a short interaction length, aiming at maximizing the re-absorption of pions and kaons produced in the intra-nuclear cascade process, which are particles considered as background for the SHiP experiment. As an additional requirement for the material selection, the target materials shall exhibit suitable physical and mechanical properties to withstand the beam-induced stresses on the target over its entire lifetime under severe conditions (irradiation, high temperatures,...).

The 400 GeV/c proton beam pulse from the SPS is foreseen to impact the target with a pulse duration of one second, delivering an average power of 2.56 MW, followed by a cooling of 6.2 seconds. Out of the 355 kW average beam power impacting on the target, roughly 305 kW will be dissipated inside the target assembly, while the rest will be lost in the surrounding shielding of the BDF target complex. A detailed list of the BDF operation beam parameters is specified in Table I.

The target is expected to survive for 5 years of operation at $4.0 \times 10^{19}$ protons on target per year, corresponding to a total of $2.0 \times 10^{20}$ protons.

II. BDF TARGET DESIGN

A. Production target material selection

The proposed target is a hybrid assembly, consisting of several collinear cylinders of TZM ((0.08%) titanium - (0.05%) zirconium - molybdenum alloy) and pure tungsten (W), clad with a W-containing Ta-alloy, Ta2.5W ((2.5%) tungsten - tantalum alloy), see Figure I. As a result, the target has a total number of nuclear interaction lengths of $\sim 12\lambda$.

- TZM is chosen for the first part of the target
### TABLE I. Baseline beam parameters of the BDF target operation

<table>
<thead>
<tr>
<th>Baseline characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton momentum [GeV/c]</td>
<td>400</td>
</tr>
<tr>
<td>Beam intensity [p+ / cycle]</td>
<td>$4 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Cycle length [s]</td>
<td>7.2</td>
</tr>
<tr>
<td>Spill duration [s]</td>
<td>1.0</td>
</tr>
<tr>
<td>Beam dilution pattern [-]</td>
<td>Circular</td>
</tr>
<tr>
<td>Beam sweep frequency [turns/s]</td>
<td>4</td>
</tr>
<tr>
<td>Dilution circle radius [mm]</td>
<td>50</td>
</tr>
<tr>
<td>Beam sigma (H,V) [mm]</td>
<td>(8,8)</td>
</tr>
<tr>
<td>Average beam power [kW]</td>
<td>356</td>
</tr>
<tr>
<td>Average beam power deposited on target [kW]</td>
<td>305</td>
</tr>
<tr>
<td>Average beam power during spill [MW]</td>
<td>2.3</td>
</tr>
</tbody>
</table>

![CERN target core diagram](image)

**FIG. 1.** Layout of the Beam Dump Facility target core. The target blocks are made of TZM or pure tungsten cylinders clad with a tantalum alloy, Ta2.5W.

The target core, that will absorb most of the beam power deposited on the target. This material has a density high enough to fulfill the experiment requirements, but leading to an energy deposition lower than for a denser material such as pure tungsten. This Mo-based alloy is chosen because it features higher strength, better creep resistance and higher recrystallization temperature compared to pure molybdenum [5].

- For the second part of the target, that will receive a lower amount of power deposition from the primary beam, pure W is selected, since it fulfills the physics requirements (high Z-number and short interaction length), and has proven good performance under irradiation [6].

The target needs to be actively cooled by water, given the high energy deposited and the high temperatures reached during operation. The cooling system design is based on the circulation of a high velocity water stream through 5 mm gaps foreseen between the different target blocks. More details about the cooling system design are given in Section [IV].

The high velocity water flow in contact with the pure W and TZM blocks could induce undesired corrosion-erosion effects. Therefore, all the target core blocks will be clad via diffusion bonding achieved by means of the Hot Isostatic Pressing (HIPing) method with Ta2.5W [7–9]. This material is selected as cladding material due to its high corrosion resistance and its convenience as high-Z material with short interaction length. Ta2.5W has enough strength and ductility to withstand the HIP conditions necessary for diffusion bonding (temperature and pressure), and is soluble with molybdenum and tungsten, so there is no risk of forming any intermetallic alloy during the HIP diffusion bonding.

In the preliminary target design phase, pure tantalum was considered as cladding material for the target core blocks, given the vast experience with tantalum-clad targets in other operating facilities such as the ISIS target stations at the Rutherford Appleton Laboratory (RAL) [10]. However, the structural calculations performed (detailed in Section [I]) have shown that the maximum stresses reached in a pure tantalum cladding may be critical for the target operation, limiting its lifetime considerably. For that reason, Ta2.5W has been considered as alternative cladding material, with the advantage of a higher strength at high temperatures and a similar corrosion-erosion resistance [5, 11]. An exhaustive R&D study has been carried out in order to test the bonding quality of Ta2.5W with TZM and pure tungsten after the HIP process. The interface mechanical tests performed have proven that the intermetallic bonding strength of TZM or W with Ta2.5W is comparable to the one with pure tantalum, validating the selection of Ta2.5W as target cladding material [9].

To further consolidate the choice of Ta2.5W for the BDF target blocks cladding, a prototype of the BDF target has been tested under beam in the North Area of CERN [12]. The target prototype consists in a scale replica of the BDF target, with identical length and reduced diameter. Pure tantalum and Ta2.5W have been used as cladding materials for the target prototype, in order to compare the performance of both materials under beam irradiation. A Post Irradiation Examination (PIE) campaign is foreseen on several blocks of the target prototype, to characterize the mechanical bonding of the cladding and core materials after irradiation. The description and results of the BDF target prototype beam tests in 2018 will be published in a dedicated paper.

**B. Optimization of the target design**

The BDF target core is made of 18 collinear cylinders with a diameter of 250 mm and variable thicknesses, from 25 mm to 80 mm for the TZM blocks and from 50 mm to 350 mm for the pure tungsten blocks, giving a total effective target core length of around 1.3 m. The target cylinders length has been iteratively adjusted to reduce the level of temperatures and stresses reached in the different materials. Table [II] summarizes the target core materials and the blocks longitudinal thickness.

![CERN target core diagram](image)

Figure [2] illustrates the maximum deposited energy density in the longitudinal direction normalized per pro-
TABLE II. Summary of the BDF final target cylinders longitudinal thickness and materials

<table>
<thead>
<tr>
<th>Block number</th>
<th>Core material</th>
<th>Length (mm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TZM</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>4</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>5</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>7</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>8</td>
<td>TZM</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>9</td>
<td>TZM</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>TZM</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>TZM</td>
<td>65</td>
<td>33</td>
</tr>
<tr>
<td>12</td>
<td>TZM</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>13</td>
<td>TZM</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>W</td>
<td>50</td>
<td>47</td>
</tr>
<tr>
<td>15</td>
<td>W</td>
<td>80</td>
<td>76</td>
</tr>
<tr>
<td>16</td>
<td>W</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>17</td>
<td>W</td>
<td>200</td>
<td>190</td>
</tr>
<tr>
<td>18</td>
<td>W</td>
<td>350</td>
<td>330</td>
</tr>
</tbody>
</table>

FIG. 2. Maximum deposited energy density per proton in the BDF target blocks along the longitudinal axis, obtained via FLUKA Monte Carlo simulations [13].

The optimization of the thickness of the target blocks is essentially based in the distribution of maximum energy deposition per block. The maximum energy values for the TZM part (first half of the target) are found in blocks 2 to 8, therefore these blocks have been segmented to have the shortest length (25 mm). The reduced thickness of these blocks allows for a more effective heat dissipation by the water flowing through the 5 mm gaps between the target cylinders, hence reducing the maximum temperatures.

The thickness of the following blocks is gradually increased as the deposited energy density is decreasing. An identical approach is used for the second part of the target (pure tungsten core): the first block is the most loaded one in terms of heat deposition, hence the thickness of this block is set to 50 mm. The length of the following tungsten core blocks is then increased progressively as the deposited energy density decreases.

As will be discussed in Section III, the most critical cladding temperatures and stresses will be reached in the upstream thin blocks (i.e. blocks 3 to 6), where the interaction with the primary beam leads to the highest values of deposited energy density. A further reduction of the target operating temperature would be possible through an additional segmentation of the low-thickness target blocks. However, the insertion of supplementary water gaps in the target design is not desirable from the physics perspective, since the presence of water gaps in the longitudinal direction reduces the effective stopping power of pions and kaons, and consequently increases the neutrino background from pion and kaon decays.

C. Dilution system requirements for target

The high energy deposited on target requires dilution by sweeping the beam over the target during the spill using upstream magnets [14], since the impact of a non-diluted beam would lead to premature failure of the target. The beam dilution pattern has been optimized taking into account the mechanical performance of the target and the different restrictions imposed by the magnets composing the dilution system in the transfer line. As a result, the SPS primary beam is foreseen to be swept following a circular pattern, with 4 turns over a 50 mm radius circle for each one second pulse.

The maturity of the current configuration is the result of an iterative process. Other beam dilution patterns have been considered for this study and included two archimedean spirals with different sweep radii and a single-turn circular trajectory. In order to evaluate the performance of the target for different dilution system designs, thermal calculations have been carried out in one of the most loaded target blocks, comparing the maximum temperatures reached after several pulses for each dilution scenario. Further details on the thermo-mechanical simulations will be given in the following section. Figure 3 presents the evolution of the maximum temperature in the Ta2.5W cladding during a one second beam pulse for different dilution scenarios.

The increase of the sweep radius reduces the maximum temperatures, as can be seen from the comparison between the 35 mm and 52 mm spiral dilution. Therefore, the dilution amplitude has been increased to the limits accepted by the upstream magnets (around 50 mm).

For an almost equivalent dilution amplitude of 50 mm, the circular sweep of the upstream magnets leads to comparable levels of temperatures in the cladding with respect to the spiral dilution pattern. The dilution system
FIG. 3. Evolution of the maximum Ta2.5W cladding temperature during the one second beam impact on target at steady state operation. Comparison between spiral and circular dilution patterns.

An increase in the number of turns reduces the maximum temperatures reached in the cladding; four circular turns have been selected as an optimal compromise between reducing temperature and stress levels and keeping the dilution frequency within reasonable limits for the dilution magnets.

The beam size has also been maximized taking into account the limitations imposed by the aperture of the upstream transfer line magnets. Larger beam spot sizes lead to lower temperatures and stresses on target, since the energy deposition is more distributed in the material volume. The compromise between maximizing the spot size of the round beam and the aperture restrictions of the transfer line magnets concluded with the selection of a beam size on target of 8 mm (1σ).

III. TARGET THERMO-MECHANICAL CALCULATIONS

A. Thermal calculations

The energy deposited by the primary proton beam on the target is evaluated with help of FLUKA Monte Carlo simulations. The energy induced by beam-matter interactions is imported into a Finite Element Analysis (FEA) software (ANSYS Mechanical) in order to evaluate the target performance during operation.

Forced convection has been applied on the surfaces of the target blocks as a boundary condition for the FEM thermal simulations, with an estimated film coefficient value of 20000 W/(m² K) and a water temperature of 30°C. This value is consistent with the average heat transfer coefficient (HTC) calculated via Computational Fluid Dynamics (CFD) simulations, as shown in Section IV.

One of the most challenging aspects of the thermal calculations performed is the implementation of the proton beam dilution into the FEM software. An ANSYS APDL code has been developed to simulate the beam sweep trajectory following a circular pattern identical to the dilution sweep design. As a result, a time-dependent temperature distribution in the target blocks is obtained (Figure 4). Table III summarizes the maximum temperatures reached in the different target materials for the most critical blocks in terms of thermal loads for each of the employed target materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Block number</th>
<th>Maximum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta2.5W</td>
<td>4</td>
<td>160°C</td>
</tr>
<tr>
<td>TZM</td>
<td>9</td>
<td>180°C</td>
</tr>
<tr>
<td>W</td>
<td>14</td>
<td>150°C</td>
</tr>
</tbody>
</table>

Figure 5 shows the maximum temperature evolution during three pulses for TZM, W and Ta2.5W, starting from a steady state condition. The effect of the beam dilution can be observed as the temperature increases in four steps during the beam pulse.

The temperature reached in the target core and cladding materials is around 0.1 Tm (melting temperature in K); these materials do not present any allotropic transformation in this range of temperatures. As a consequence, the evolution of the physical and mechanical properties with temperature is expected to evolve gradually, without abrupt changes. However, there are several limitations associated with the high temperatures expected during operation.

First, the degradation of the material properties at high temperatures, specially for Ta2.5W, leads to a reduction of the strength of the material (see Section III B). Furthermore, it is undesirable to reach temperatures above the boiling point of water on the target surface, which could lead to localized boiling of the cooling water, inducing a severe degradation of the heat dissipation from the blocks. This issue will be reported in more detail in Section IV. Finally, the thermal loads applied to the target are responsible for high levels of stresses, in particular for the cladding material where the increase of temperature after each proton beam impact can reach up to 120°C, as shown in Figure 5.
FIG. 4. Temperature distribution in the BDF target at the end of the one second long spill. The effect of the BDF beam dilution system can be clearly appreciated: four beam sweep turns in one second over a 50 mm radius circular pattern.

FIG. 5. Maximum temperature evolution during three beam pulses after long-time operation for the BDF target materials, starting from a steady state condition. The results are shown for the most loaded target blocks.

B. Structural calculations

1. Target materials properties review

For an accurate simulation of the materials behaviour during the target operation, it is important to take into account the changes in the material properties as a function of temperature. The strength of the target materials is a crucial parameter when estimating the target lifetime, and thus, when designing the target assembly.

As a general trend, for the three materials, the yield and tensile strength decrease with temperature [15–17]. Ta2.5W shows much lower strength values than TZM and W over the entire range of temperatures. It must be noted that the differences in mechanical properties between products of the same material can be significant and they highly depend on the geometry and manufacturing process applied.

The most relevant values of yield and tensile strength that have been measured or found in literature are presented below:

- The yield and tensile strength of Ta2.5W were measured at room temperature for specimens obtained from Ta2.5W disks treated with a HIP cycle identical to the one used to produce the BDF target blocks. The measured yield strength was 270 MPa, and the tensile strength 360 MPa [18]. For comparison purposes, pure tantalum specimens with identical geometry have also been tested after the HIP process, showing much lower yield strength (170 MPa) and tensile strength (220 MPa). This low strength exhibited by pure tantalum would probably compromise the target lifetime as mentioned in Section II.A.

- Yield strength values of Ta2.5W sheets at the target operational temperatures can also be obtained from Ref. [17], which reports values at room temperature which are similar to the ones measured for Ta2.5W disks post-HIP process. Values at high temperature are also reported: the expected yield strength of Ta2.5W at 200°C is 190 MPa.

- Regarding TZM, samples obtained from a 200 mm diameter, 100 mm long rod were tested at 20 and 700 °C [19]. At room temperature, the measured yield strength and mean tensile strength were 480 and 525 MPa respectively. At 700 °C, the measured yield strength is 290 MPa. These values are significantly lower than the ones usually found in literature, as in Ref. [15]. This is probably due to the bigger grain size obtained in the production of rods with such a large diameter and length, which
is also the case of the TZM rods produced for the BDF target. Considering the reduction of material strength with temperature reported in Ref. [15], the estimated yield strength at 200°C is assumed to be around 430 MPa.

- Pure tungsten presents brittle behaviour at room temperature, and for common commercial tungsten products the ductile-to-brittle-transition temperature (DBTT) is around 300°C in most cases [20, 21]. It is therefore foreseen that the BDF target tungsten will operate in the brittle regime, as the maximum temperatures are expected to be around 150°C. Tensile testing on tungsten specimens produced via sintering and HIP has been carried out in Ref. [22], measuring an Ultimate Tensile Strength (UTS) at room temperature of 570 MPa. This value is relevant to the BDF target material properties study, given that the large diameter and length of the BDF tungsten blocks will most probably constrain the choice of the tungsten cylinders’ production procedure to the sintering and HIP method instead of forging or rolling (see Section V).

A reduction of the tensile strength of tungsten at 150°C to 60% of the UTS at room temperature has been reported in [16]. Taking into account this reduction of strength, the estimated UTS at 150°C is assumed to be around 330 MPa.

From a radiation damage standpoint, the target materials are expected to receive up to 0.5 DPA over the expected lifetime of the facility. Due to the beam dilution on target, a large volume of the core will be affected by radiation damage, e.g. more than 4000 cm³ are expected to receive above 0.05 DPA per year. Given that a bulk material damage (and not only a superficial or limited volume damage) is foreseen, the effect of irradiation on the target materials has been identified as a potential issue for the target operation.

It is expected that TZM and tungsten will undergo radiation hardening with a pronounced brittle behavior after a few years of operation [23, 24]. The increase of strength is regarded as beneficial, but the materials embrittlement could be harmful for the target lifetime, due to easier crack propagation and higher sensitivity to defects. A high safety factor is required for these materials in terms of static stress and fatigue life in order to increase operational robustness. Ta2.5W has been reported to maintain its ductility and increase slightly its strength after irradiation, especially if high purity material is used [25, 26].

Further studies are required to evaluate the effect of irradiation on the thermo-physical properties of the BDF target materials. As an example, the degradation of the thermal conductivity of tungsten after proton irradiation has been reported in Ref. [27], and it shall be studied if the Coefficient of Thermal Expansion (CTE) of the target materials will also be affected in a detrimental manner by radiation damage. An irradiation program has been launched in order to assess this.

2. Finite Element Model (FEM) simulation results

The stresses induced by the high temperatures reached in the target materials have been estimated by means of FEM calculations. The preliminary simulations performed have shown that the level of stresses is substantially reduced if the target blocks are allowed to expand freely after the temperature rise generated by the beam impact. Therefore, in the analysis the target cylinders are considered to be resting on the support (not fixed or constrained). A detailed description of the target mechanical assembly will be given in Section V.

The temperature distribution for each of the blocks has been imported as a thermal load for the structural analysis. A transient structural analysis has been performed to evaluate the stress evolution over time for a given temperature distribution at each time step. The slow application of thermal loads (due to the pulse duration of one second) allows inertia effects to be neglected; for that reason the structural analysis can be regarded as quasi-static.

Ta2.5W and TZM present ductile behaviour at the target’s operational temperatures, and if the yield points of the materials are reached, the blocks will start deforming in the plastic regime. However, the cyclic plastic deformation of the core or the cladding during a long period could lead to premature fracture of the material and/or to detachment of the cladding with respect to the base refractory metal, reducing or blocking the heat dissipation through the cladding material. Therefore, plastic deformation is undesirable, and the von Mises yield criterion has been used to evaluate the safety margin of the stresses reached in the Ta2.5W cladding and TZM core with respect to the temperature-dependent yield strength of these materials.

After a few years of operation, embrittlement of the TZM core is expected due to radiation damage; no plastic deformation is foreseen at that point for TZM. Since the TZM strength will also be increased, the comparison of the von Mises equivalent stress with the yield strength under un-irradiated conditions is assumed to be a conservative approach.

For pure tungsten, which is considered as a brittle material at the target operational temperatures, the Chris-tensen criterion [28] is considered the most suited failure criterion. However, due to the low availability of compressive strength data for tungsten under the target operational conditions, the maximum normal stress criterion has been used to assess if the maximum stresses reached in the tungsten core are within the safety limits of the material.

Table IV summarizes the maximum stresses calculated for each material, as well as the safety margin with respect to the yield strength or ultimate tensile strength of
the material at the operational temperatures.

Table IV. Maximum stresses reached in the BDF target materials and safety factor with respect to the material limits reported in literature [18, 19, 22].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TZM</td>
<td>128</td>
<td>430</td>
<td>3.5</td>
</tr>
<tr>
<td>Ta2.5W</td>
<td>95</td>
<td>190</td>
<td>2</td>
</tr>
</tbody>
</table>

The stress distribution in the most loaded blocks is shown in Figure 6, where the influence of the beam dilution system can be clearly appreciated. The beam sweep following four circular turns is also noticeable in Figure 7, the stress value in a particular location increases as the beam approaches the analyzed point and decreases as the beam moves away.

As discussed in Section II B, the largest values of stress are found in the upstream thin blocks (3 to 6). The stress distribution inside one of the most critical target blocks is displayed in Figure 8, showing an abrupt variation of the von Mises equivalent stress in the interface between the target cladding and the core. For all the target materials, the maximum stresses are well within the material limits. The target Ta2.5W cladding, with a lower safety factor with respect to the design criteria, is considered to be one of the most critical parts of the target.

C. Fatigue analysis

1. Fatigue literature review

The SPS primary beam is foreseen to impact the BDF target for one second every 7.2 seconds, and the total number of cycles expected during the target lifetime is of the order of $10^7$. This means that the target will operate under cyclic structural loads, and it is necessary to evaluate the fatigue life of the target materials under high-cycle loading.

A literature review has been carried out to obtain fatigue data for the target materials under loading conditions similar to the BDF target ones. Studies on fatigue life are very limited for tungsten, TZM and tantalum (alloyed or un-alloyed), especially for fatigue behaviour at high temperatures and under irradiation. This makes the estimation of the fatigue properties for the BDF target materials difficult, as the different material and test conditions (geometry, heat treatment, purity, test mode, test stress ratio, test temperature, test frequency...) can considerably change the resulting fatigue strength value.

Table V summarizes the values of fatigue data which are considered to represent the closest conditions to the BDF target operation. Nevertheless, it is worth mentioning that some of the test conditions are not identical to the ones of the BDF target materials (e.g. fatigue data given at room temperature, different material production route, etc.).

It can be seen that TZM has the highest fatigue strength at $N = 10^7$ with 440 MPa at room temperature, and the fatigue limit decreases at high temperatures as expected. Pure tungsten exhibits the lowest fatigue strength (180 MPa) for the sintered and HIPed manufacturing route, which is considered closer to the BDF target case. It is worth noting that the measured fatigue strength can be considered as conservative, since all the tests presented in Ref. [22] were carried out in the tensile regime, and are assumed to lead to lower values than for fully-reversed loading. Ta2.5W shows a fatigue strength of 310 MPa at room temperature, which is relatively close to the tensile strength of the material (85% of the UTS at room temperature).

2. Fatigue simulation results

As a result of the high temperatures reached during operation for every beam impact on target, the target materials are subjected to large mean stresses and stress amplitudes. The fatigue data found in literature is usually obtained from uniaxial fully-reversed tests (with a mean stress equal to zero). However, the state of stresses in the target blocks is multiaxial and with a non-zero mean stress. In order to correlate the stresses calculated for the BDF target with the available fatigue strength, a two-step approach is necessary:

- Firstly, an equivalent mean stress and an equivalent stress amplitude must be calculated, that are expected to give the same fatigue life in uniaxial loading as the multiaxial stress-state found in the target.
- Secondly, an equivalent fully-reversed stress needs to be computed from the values of equivalent mean stress and equivalent stress amplitude. This equivalent fully-reversed stress must take into account the contribution of the mean stress to the fatigue life of the target materials, in order to compare it with the fatigue strength under fully-reversed loading found in literature.

For TZM and Ta2.5W, which are considered as ductile materials, the Sines method [30] has been regarded as the most suited for this analysis. However, given the low availability of fatigue strength data under loading with non-zero mean stresses for the target materials, a similar approach requiring only data for fully-reversed fatigue has been adopted.
FIG. 6. Von Mises equivalent stress or maximum principal stress distribution after one beam pulse in the most loaded blocks for each target material. (a) Ta2.5W cladding of block #4, maximum equivalent stress (95 MPa) reached in the beam impact region at the interface with the block core. (b) TZM core of block #4, maximum equivalent stress (130 MPa) found in the core centre (mainly due to high compressive stresses) and in the interface with the tantalum cladding. (c) W core of block #14, highest value of maximum principal stress reached in the upstream face of the block, following the beam dilution path.

TABLE V. Summary of the reviewed high-cycle fatigue data relevant for the BDF target operational conditions. Sources: TZM [29], W [22], Ta2.5W [5]. P/M: Powder Metallurgy, Aw: As worked, HIP: Hot Isostatic Pressing, Rxx: Recrystallized, RT: Room Temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Production process</th>
<th>Dimensions</th>
<th>Test mode</th>
<th>Number of cycles</th>
<th>Stress ratio, temperature, frequency (Hz)</th>
<th>Fatigue limit (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TZM</td>
<td>P/M, Aw Ø50 mm bar</td>
<td>Push-pull</td>
<td>$10^7$</td>
<td>-1, RT, 25</td>
<td>-1, 850°C, 25</td>
<td>440</td>
</tr>
<tr>
<td>W</td>
<td>Sintered + HIP Ø5 mm bar</td>
<td>Push-pull</td>
<td>$2 \cdot 10^6$</td>
<td>0, RT, 25</td>
<td></td>
<td>180</td>
</tr>
<tr>
<td>Ta2.5W</td>
<td>Sintered + HIP Ø5 mm bar</td>
<td>Push-pull</td>
<td>$2 \cdot 10^6$</td>
<td>0, RT, 25</td>
<td></td>
<td>350</td>
</tr>
</tbody>
</table>

FIG. 7. Evolution during the one second SPS beam pulse of the von Mises equivalent stress (TZM and Ta2.5W), and maximum principal stress (pure tungsten). The results have been plotted for the locations of maximum stress shown in Figure 6.

The octaedral shear stress (von Mises) theory applied to a multiaxial state of stresses has been used to calculate the equivalent stress amplitude $\sigma_{q,a}$ and the equivalent mean stress $\sigma_{q,m}$ from the evolution of principal

FIG. 8. Stress distribution in the longitudinal (Z) axis at the beam impact position (Y = 50 mm) for block #4. Stress calculated at the end of the one second beam pulse on target.
FIG. 9. Graphic representation of the evolution during three consecutive beam pulses (after steady state operation) of the equivalent mean stress and stress amplitude. The equivalent stresses presented are obtained from the principal stresses in the locations of maximum stress (Figure 6) of each material.

The modified Goodman equation (Equation 1) has been used to compare the stresses calculated for the BDF target materials which have a non-zero mean stress, with the fully-reversed stress amplitude found in literature. This equation relates the equivalent mean stress $\sigma_{q,m}$ and equivalent stress amplitude $\sigma_{q,a}$ with an equivalent fully-reversed stress amplitude $\sigma_{q,f}$ which is assumed to give the same fatigue life:

$$\sigma_{q,f} = \frac{\sigma_{q,a}}{1 - \frac{\sigma_{q,m}}{\sigma_{UTS}}} \leq \sigma_{fat},$$

where $\sigma_{UTS}$ is the Ultimate Tensile Strength of the material, which has been taken for the present calculations from the measured values at room temperature cited in Section III B and $\sigma_{fat}$ is the fatigue limit of the material. The results of the calculations performed are summarized in Table VI.

The stresses found in the BDF target are well within the endurance limits found in literature. The thermomechanical calculations performed have proven that it is unlikely that the target blocks will fail due to high-cycle fatigue. In this case the Ta2.5W cladding is not a critical aspect for the target operation, which is due to the fact that the fatigue limit of the material is relatively close to its tensile strength.

Further studies are required to evaluate the effects of radiation damage, as it could eventually reduce the fatigue life of the target, even though the safety margin is relatively large. Additional fatigue data under more representative loading conditions are necessary for an accurate estimation of the target materials fatigue life under operational conditions and will be performed in the future.

IV. TARGET COOLING SYSTEM

A. Cooling system design

The target cooling system is one of the most critical parts of the BDF target design, given the high energy deposited on target during operation. Pressurized water has been chosen as cooling medium, other coolants such as air or helium would require a much higher flow rate to...
dissipate such a considerable amount of power. Several requirements have been considered for the cooling system design: first, a high water velocity is necessary to obtain an effective HTC between the cooling medium and the target blocks. Then, the pressure of the circuit should be high, and the pressure drop minimized, in order to ensure that the water in contact with the solid blocks is always below the boiling temperature. Furthermore, the cooling system design has been optimized in order to limit the increase of temperature in the circulating water, whilst minimizing the necessary flow rate.

Figures 10 and 11 illustrate the cooling system circulation path around the target blocks. The target cylinders are separated by 5 mm channels that allow water passage between the blocks. The water circulation is aimed at cooling down all the flat faces of the target cylinders, since they are impacted directly by the diluted beam and will therefore reach the highest temperatures during operation. The proposed cooling system design consists in a serpentine configuration (series flow) with two parallel streams. The serpentine circulation can provide high water speeds in the channels with a relatively low flow rate.

The two-parallel-stream configuration aims at reducing the total pressure drop of the circuit and the temperature increase of the water from inlet to outlet. Another reason for this arrangement is to avoid a cooling circuit failure in the event that one of the channels is blocked, due to swelling of the blocks due to thermal expansion or debris in the circuit. If one of the channels is blocked, the water flow can continue through the other parallel channels, improving the circuit reliability. The last three channels are set in parallel, given that the number of channels is odd and the last tungsten blocks are the ones receiving the lowest amount of energy.

The channels are connected by "manifolds" that receive the water from two channels and distribute it to the following two. The manifold size is reduced to minimize the total water volume of the cooling circuit, and is constrained by the target support design, that will be described in Section V. The serpentine circulation is horizontal, from the left side of the blocks to the right side and vice versa; and is ensured by the presence of "blockers" after every two channels. This configuration has been chosen profiting from the experience of the target prototype cooling system design [12], where the series circulation of water was designed to be vertical (bottom-top-bottom), leading to the formation of air pockets during the filling process and to stagnant water in the bottom after drainage.

A high pressure of 22 bar is selected to raise the water boiling point above 200°C and avoid localized boiling during operation. The main risk of having localized boiling is the loss of heat transfer between the solid blocks and the water, which would prevent the heat dissipation by convection.

It is desired to have a relatively uniform water velocity in the channels of around 5 m/s. Higher water speeds could lead to undesired erosion-corrosion effects on the Ta2.5W cladding surface. As will be shown in the following sections, the average HTC obtained with a velocity of 5 m/s in the channels is sufficiently high to ensure temperatures and stresses well within the operational limits of the target.

B. Analytical calculations

Based on the fundamental knowledge of flow dynamics and heat transfer, analytical calculations have been performed in order to have a preliminary idea of the water flow behaviour in the cooling channels and the manifold.

A channel velocity of 5 m/s has been considered as the initial design parameter. Due to the serpentine nature of the flow, the sum of mass flow rate in any couple of parallel cooling channels is identical and is also equivalent to the inlet mass flow rate. However, in the last part of the cooling domain, three channels are in parallel and therefore the average velocities in these channels will be less than 5 m/s. Using the principle of mass conservation, the inlet mass flow rate can be calculated. The cross-
section area of the cooling channels can be simplified as a rectangular cross-section with a channel thickness of 5 mm and a width of 180 mm. The required water flow rate for an average water speed of 5 m/s is around 9 kg/s, which is considered to be admissible from the cooling system design point of view.

Using the energy balance equation, the temperature rise of the water from the inlet to the outlet of the flow configuration can be obtained from the average beam power on target (305 kW). An acceptable temperature increase is expected in the cooling circuit during operation, with values around 8°C.

The average Reynolds number inside the channels is around 60000, showing that the flow is highly turbulent in the cooling circuit channels. The water properties considered have been taken at 30°C and 20 bar, which are assumed to be the average fluid temperature and operational pressure respectively. The HTC at the fluid-solid interface can be analytically calculated using the following expression:

$$ h = \frac{N_u D \times k}{D_H} \quad (2) $$

where $k$ is thermal conductivity of the water, $D_H$ is the hydraulic diameter of the channel and $N_u D$ is the Nusselt number. Several convection correlations can be used to calculate the value of $N_u D$ for turbulent flow in a channel. Assuming water flow over a smooth surface, Gnielinski’s equation can be used [31]:

$$ N_u D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{1/3} - 1)} \quad (3) $$

which is valid for, $0.5 \leq Pr \leq 2000$ and $3000 \leq Re_D \leq 10^6$. $f$ is the friction factor which can be calculated by Petukhov’s relationship [32]:

$$ f = (0.79 \ln(Re_D) - 1.64)^{-2} \quad (4) $$

valid for $3000 \leq Re_D \leq 5 \times 10^6$. Considering an average velocity of 5 m/s in the channels, the friction factor is found to be $f = 0.02$.

The Prandtl number considered for water at 30°C is 5.4 [31], and is assumed to be constant for the flow. The Nusselt number is then calculated from Equation (3) with a value of 350.

The estimated average value of HTC in the fluid-solid interface of the target channels obtained from Equation (2) is 22000 W/(m² K). The high HTC value computed is attributed to the large velocities reached in the channels.

The analytic calculations gave a broad idea about the flow and heat transfer characteristics in the cooling circuit and specifically in the cooling channels. In spite of that, an extensive CFD study of the full scale cooling system was needed given the complexity of the flow in the turbulent regime, in order to resolve the flow and heat transfer in the boundary layer of the channels.

C. CFD calculations

A commercial CFD code, ANSYS Fluent©, has been used to perform the extensive 3D turbulence modelling of the flow configuration. A non-uniform energy deposition map imported from the FLUKA MonteCarlo [13] simulation results has been applied to all the target blocks in the ANSYS Fluent model. In conjugate heat transfer problems (like the present one), the heat transmitted from the solid body to the liquid is highly dependent on the thermal boundary layer. Therefore, a sophisticated turbulence model, $k – \omega$ SST, has been used to resolve the boundary layers.

1. Steady-state results

Steady-state simulations have been carried out in order to investigate the flow behaviour in the cooling circuit and the target. The estimated pressure drop in the circuit is 3.2 bar, which means that the absolute pressure at the outlet of the target cooling circuit is around 19 bar. The boiling temperature at this pressure is over 200°C.

Figure 12 illustrates the velocity contour in the target cooling circuit along the longitudinal plane. It can be seen that the average velocity in all the cooling channels stands between 4 to 6 m/s, except for the last three channels where the average velocity is around 3 to 4 m/s.

As the water stream enters the target cooling circuit from the inlet, the flow is split into two streams that enter the channels with similar mass flow rate. As a result, the average velocity in the first two cooling channels is almost identical. However, due to the presence of blockers (which make the serpentine design possible), the mass flow rate in the even channels is higher than the one of the odd channels. This twisting effect can be appreciated in Figure 13.

FIG. 12. 2-dimensional velocity contour in the target cooling circuit along the longitudinal plane. The water speed in all but the last three channels is relatively uniform around 5 m/s.

The total temperature rise at the outlet obtained from the steady-state CFD simulations performed is around 8°C (Figure 14), which is found to be in good agreement with the temperature rise calculated from the energy bal-
FIG. 13. Variation of average velocities in the target water channels. The trendline of the plotted values is represented by a dotted line, and stands close to the desired water velocity of 5 m/s.

FIG. 14. Temperature contour in the cooling circuit along the YZ plane. Results from steady-state thermal CFD simulations. Total temperature increase $\approx 8^\circ$C. However, the transient calculations have shown that the outlet temperature is expected to present small fluctuations influenced by the beam impact on target. Figure 15 displays the average heat transfer coefficient for all the 19 channels of the cooling domain. The computed HTC shows a good agreement with the analytical values for each channel. As shown by the trendline of the HTC calculated via CFD simulations, the average HTC in the target cooling channels stands slightly above 20000 W/(m$^2$ K), as predicted by the analytical calculations.

2. Transient results

CFD transient calculations have been performed to reproduce the target behaviour during the one second SPS primary beam impact on target and the subsequent 6.2 seconds cooling, thereby replicating the 7.2 seconds BDF cycle. Unlike in the thermal simulation setup shown in Section III A, the time-dependent beam sweep over the one second spill is not taken into account, instead a circle-shape energy distribution corresponding to the circular dilution path is directly applied on the target blocks.

Figure 15 illustrates the temperature distribution contour in a longitudinal section through all the target blocks at the end of the proton pulse (1 second) during steady state conditions, with the HTC evaluated from CFD simulations. The maximum temperature expected is around 160$^\circ$C, found in blocks 9 and 12.

The maximum temperatures in both cases are found in the TZM core of blocks 9 and 12, with temperatures around 160$^\circ$C for the CFD calculations. In the tungsten core, the maximum temperatures are located in the first tungsten block, reaching around 130$^\circ$C. The temperature reached in the Ta2.5W cladding, which is considered one of the most critical elements for the target design, is about 120$^\circ$C for the CFD calculations, and is found in
the cladding of block 3.

The temperature profile obtained for the FEM and CFD simulations is qualitatively similar, but the maximum temperatures expected from the CFD simulations are lower. This difference can be explained by the higher accuracy in the calculation of the HTC for the CFD simulations compared with the constant convection coefficient employed in the FEM analysis.

It can be concluded that the structural stresses calculated in Section III B by importing the temperatures obtained via FEM calculations are conservative, and the safety margins with respect to the material limits are expected to be even higher.

Figure 18 presents the maximum surface temperature calculated for each target block. The maximum surface temperature is around 90°C, which is less than half of the boiling temperature of water at the outlet pressure (above 210°C). From these results, it can be concluded that water boiling is not likely to occur during normal operation of the BDF target.

D. Considerations about loss of coolant accidents

The target cooling circuit is critical for the successful operation of the BDF target. A disconnection or rupture of the cooling pipes or a failure of the cooling system equipment could lead to the sudden stop of the water circulation or to the loss of cooling water in the circuit. In the event of a Loss Of Coolant Accident (LOCA) with beam stop, the heat produced by the decay of the long-time irradiated target materials will dissipate at a very slow rate, due to the absence of forced cooling, increasing the temperature of the target materials for the hours and days following the accident. The main risk is the possible melting of the target materials given the high concentration of heat in the target or the production of tungsten trioxide (WO₃) species, which are highly volatile [33].

The decay heat produced in the target materials for different periods has been estimated by FLUKA simulations, and thermal calculations have been carried out to evaluate the effects on target of a cooling system failure. Figure 19 presents the maximum temperature evolution in the target blocks after the cooling system failure during two years. Decay heat measurements have been performed for the neutron spallation target of ISIS (RAL, UK), and a similar trend has been reported [34]. The maximum temperature in the target blocks is around 350°C and is reached one week after the accident, which is sufficiently low to avoid melting of the target materials as well as oxidation even in the case of breached tungsten. Further studies are required in order to understand the possibility for producing oxidation at these temperatures in TZM or Ta2.5W.

The stresses induced by the thermal loads have also been calculated, concluding that the level of stresses is not critical in terms of fracture of the target materials, but could induce plastic deformation in the Ta2.5W cladding of some of the blocks. In order to achieve an accurate modelling of the air, helium or water behavior after a cooling system failure accident, CFD studies applied to this specific case are necessary.

V. TARGET ASSEMBLY MECHANICAL DESIGN

The BDF target assembly consists of four main parts: the target blocks, an inner tank that supports the target blocks, a leak-tight outer tank that encloses the inner tank, and a helium container that contains the whole assembly. A section of the inner and outer tank supporting the target blocks can be seen in Figure 20. The helium
FIG. 19. Evolution of the maximum temperature in the different target materials after a cooling system failure due to the decay heat generated inside the target (logarithmic scale).

container enclosing the full target assembly is shown in Figure 21.

A. Target blocks production

The BDF target core blocks consist of two different parts:

- A TZM or W cylinder with different length according to the block position in the target core. Preliminary investigations have shown that all the TZM cylinders can be manufactured via multi-axial forging, while not all the pure tungsten cylinders can be obtained by this method [35]. The length of some of the tungsten cylinders, that reach up to 350 mm long, is a limiting factor to apply longitudinal forging. For that reason, it is foreseen to produce the W cylinders via sintering and HIPing, this process leading to an isotropic material structure and an acceptable density of around 97%.

- A cladding made out of Ta2.5W, which encloses the TZM or W cylinder, and consists of a tube with variable length and two disks. The Ta2.5W tubes can be rolled, and must be seamless as this is a requirement for the HIP process that will be described later on. The Ta2.5W disks can be obtained by forging.

For the production of the target blocks, the TZM or W cylinder is inserted into the Ta2.5W tube and closed above and below by the two Ta2.5W disks. The disks and the cylinder have to be precisely machined to ensure a gap of around 0.1 mm between the disk and cylinder diameters and the inner diameter of the Ta2.5W tube. This gap should be sufficient for the disks and cylinder insertion into the Ta2.5W tube, and tight enough to achieve the diffusion bonding between the materials during the HIP process. More details about the HIP assisted diffusion bonding carried out for the target blocks production are given in Ref. [9].

As an example, Figure 22 shows the different parts necessary for the production of the target blocks, in this case for the production of a reduced scale target block (25 mm thickness, 80 mm diameter) for the BDF target prototype tested in the North Area of CERN [12].

Before the HIP run, the top and bottom Ta2.5W disks are electron-beam (EB) welded to the Ta2.5W tube, and the whole assembly is tested under vacuum to guarantee the leak-tightness of the capsules. After that, the capsules are covered with an Argon foil to prevent oxidation. Then, every assembled target block undergoes a HIP cycle, reaching a temperature of 1200°C and a pressure of 150 MPa for 2 hours. The HIP process carried out for the BDF target blocks production is crucial to ensure the mechanical and chemical bonding between the cladding and core materials [9]. Once the HIP cycle has been completed, the target blocks have to be machined to ensure that the design dimensions are respected.

B. Target vessel inner stainless steel tank

The inner tank is composed of several "supports" that are assembled together. Each target block has its own support, that is acting at the same time as a handling tool. Figure 23 shows a description of the supports that make up the inner tank. The target blocks can weigh up to 300 kg for the heaviest tungsten cylinder, making it necessary to have a handling mechanism for their assembly. Each support holds the corresponding target block in a vertical position during assembly (Figure 24), and all the supports are stacked on top of each other starting from the first support (Figure 25).

The supports are progressively screwed to each other, making one whole supporting structure. Once the assembly is completed, the target blocks supporting structure (hereafter, inner tank) is placed in horizontal position for the subsequent operation. The inner tank structure is held by the first support in one side and by the outer tank downstream flange in the other side. The structure has been designed to safely withstand the weight of all the target blocks, with an acceptable vertical deformation in the centre. Figure 26 presents a longitudinal cross-section of the inner tank structure in horizontal position, the target blocks can be seen enclosed by the different supports, as well as the outer tank containing the whole assembly.

Another function of the inner tank is to enclose the target cooling circuit. The different supports include dedicated grooves in order to provide the foreseen circulation path for the water cooling, compatible with the cooling system design presented in Section IV. The inlet is placed at the bottom of the first support, making it the lowest point of the whole cooling circuit. This arrangement per-
FIG. 20. Longitudinal section of the BDF target inner and outer tank structure. The target blocks supported by the inner tank can be seen, as well as many functional elements of the cooling circuit and the supporting structure of the target itself.

C. Target vessel outer stainless steel tank

The outer tank is responsible for providing leak-tightness to the target assembly, and structural stability to the equipment. The cooling circuit is enclosed by the inner tank, that is - by design - not sealed against water leaks. The outer tank is welded to the first support at one end, and to the downstream flange at the other end (Figure 20). Regarding the assembly procedure, once all the inner tank supports are stacked and screwed one on top of each other, the outer tank is inserted and welded to the first inner tank support. The fact of having only two welds adds simplicity and robustness to the target manufacturing and assembly process, while ensuring a good reliability of the system.

In order to avoid any stagnation of water between the inner and outer tank, a sufficiently large gap is foreseen to force the water circulation in the volume between both tanks, creating an "external" cooling loop, which can be seen in Figure 20. The outer tank diameter has been optimized via CFD calculations, minimizing the pressure drop in the external circuit while keeping an acceptable water speed.

Figure 20 shows the layout of the first support of the inner tank, one of the key elements of the target assembly. This support acts as upstream flange of the outer tank, and includes both the internal cooling circuit inlet and the external cooling circuit outlet.

The first support assembly includes also the proton...
FIG. 23. Description of one target block support, part of the target inner tank. Each support integrates different elements that permit the assembly with the previous and following supports, as well as the water circulation around the target blocks.

FIG. 24. Handling process of the target blocks: each target block is lifted by the corresponding support, which includes a dedicated interface for the target blocks handling operation.

FIG. 25. Target inner tank assembly process and outer tank fitting: (i) each support is mounted on top of the previous one in vertical position; (ii) once all the supports have been assembled, the outer tank is installed and welded to the first support, enclosing the whole inner tank; (iii) the whole assembly is placed in horizontal position (Figure 20).

FIG. 26. Layout of the first support of the target inner tank, also functioning as upstream flange of the outer tank and beam window.

beam window. The thickness of the central part of the first support, where the diluted beam impact will take place, has been optimized to obtain a beam window thick enough for a good mechanical reliability, taking into account the internal pressure of 22 bar; and thin enough to avoid critical levels of energy deposition by the beam impact.

D. Target helium tank

The whole target assembly is contained inside a square-section tank filled with inert gas (He at the current stage), as shown in Figure 21. The presence of helium gas ensures a dry and controlled environment for the target operation, reducing the corrosion effects on the target assembly components. Additionally, the closed circulation of helium allows the monitoring of possible water leaks from the target vessel.

In case of target failure, it is foreseen to replace the whole helium container with the internal components. A comprehensive study of the target complex handling and integration has been performed and reported in detail in a separate publication [36]. The target assembly design is fully compatible with the target complex integration, that foresees the target helium container remote disconnection and exchange. All the electrical, water and helium interfaces of the helium tank that can be seen in Figure 21 have been designed to be disconnected via remote handling, and are detailed in [36].
VI. CONCLUSIONS AND FUTURE WORK

In the framework of the Beam Dump Facility comprehensive design study phase, a design of the target system has been developed. Based on the experimental requirements of the facility, a solution consisting in a dense target/dump made of several blocks of TZM and pure tungsten clad with a thin layer of tantalum-tungsten has been conceived. A target composed of several collinear cylinders segmented in an optimized manner is foreseen, and a fast circular beam dilution system has been selected in order to deal with the challenging levels of heat and energy deposition induced by the SPS proton beam interaction. Extensive thermo-mechanical studies have been carried out to evaluate the target reliability under the high temperatures, stresses and high-cycle loading to which the target will be exposed during its lifetime. The most critical element in the target assembly is the Ta2.5W cladding, which is expected to reach temperatures close to 200°C and cyclic stresses of around 100 MPa. The thermal and structural analysis performed have proven that the safety margins achieved with respect to the material limits are sufficiently high, validating the proposed target design and material selection. The heat dissipation being a key factor in the target survivability, a high-speed water cooling system is foreseen. Detailed CFD calculations have demonstrated that the high velocities reached in the gaps between the target blocks will lead to an effective heat dissipation from the target, and that the cooling system configuration is fully compatible with the operational requirements. Finally, a preliminary design of the target assembly has been executed, and the manufacturing, handling and assembly processes have been assessed, confirming the feasibility of the whole target assembly.

VII. ACKNOWLEDGMENTS

The authors express their thanks to the Physics Beyond Colliders Study Group (specifically the Beam Dump Facility Project group) for the support in the execution of the activity. The authors would also like to thank Dan Wilcox (ISIS/RAL, United Kingdom) for technical exchanges and valuable discussions.