Design and operation of the air-cooled beam dump for the extraction line of CERN’s Proton Synchrotron Booster (PSB)


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ABSTRACT: A new beam dump has been designed, built, installed and operated to withstand the future proton beam extracted from the Proton Synchrotron Booster (PSB) in the framework of the LHC Injector Upgrade (LIU) Project at CERN, consisting of up to $1 \times 10^{14}$ protons per pulse at 2 GeV, foreseen after the machine upgrades planned for CERN’s Long Shutdown 2 (2019-2020).

In order to be able to efficiently dissipate the heat deposited by the primary beam, the new dump was designed as a cylindrical block assembly, made out of a copper alloy and cooled by forced airflow.

In order to determine the energy density distribution deposited by the beam in the dump, Monte Carlo simulations were performed using the FLUKA code, and thermo-mechanical analyses were carried out by importing the energy density into ANSYS®. In addition, Computational Fluid Dynamics (CFD) simulations of the airflow were performed in order to accurately estimate the heat transfer convection coefficient on the surface of the dump.

This paper describes the design process, highlights the constraints and challenges of integrating a new dump for increased beam power into the existing facility and provides data on the operation of the dump.

KEYWORDS: Accelerator Applications, Overall mechanics design (support structures and materials, vibration analysis etc), Targets
1 Introduction

The Proton Synchrotron Booster (PSB) has accelerated protons as part of CERN’s accelerator complex for more than 40 years [1]. Ever since its construction, the accelerator has undergone several upgrades that have made possible, among other aspects, drastic increases in both the extracted intensities and extraction energies. From the $5.4 \times 10^{12}$ protons per pulse (ppp) extracted at 800 MeV in late 1973 [2], in recent years the Booster has accelerated up to $4 \times 10^{13}$ ppp at an energy of 1.4 GeV. Moreover, as a result of the LHC Injector Upgrade (LIU) project at CERN [3], foreseen...
after the machine upgrades planned for CERN’s Long Shutdown 2 (LS2, 2019-2020), the Booster will be able to accelerate up to $1 \times 10^{14}$ ppp at 2 GeV.

It was in the framework of this series of upgrades that the dump was replaced in October 2013, during CERN’s Long Shutdown 1 (LS1, 2013-2014). The previous dump had in fact been operating since the construction of the PSB in 1972 and could no longer safely absorb the beams of increased intensity and energy accelerated by the booster.

The aim of this manuscript is to present the R&D activities for the new design of the dump, describing how it can cope with the upgraded beam parameters, as well as the procedure for its replacement, taking into consideration the radiological requirements along with the physical and infrastructural constraints inherent of the project. In the last section, the operational feedback from the use of the dump between LS1 and LS2 are compared with the finite-element simulations that guided the design of the dump.

1.1 The Previous Dump Core

As shown in Figure 1, the previous dump core consisted of a series of 13 Fe37-steel [4] disks, assembled in decreasing order of thickness along the beam axis, from 100 down to 2 mm, with a constant gap of 4 mm between each of them [5]. This assembly had a total length of 489 mm and a diameter of 220 mm.

The dump was cooled by means of a single contiguous stainless steel cooling pipe running forwards and backwards six times through the disks at different angular positions. In the last years of operation, however, the cooling pipes were disconnected when water leaks were detected. Since the dump core was not under vacuum and was exposed to the atmosphere, natural air convection was left as the only means of evacuating the heat deposited in the core. Moreover, the beam pipe that was inserted in the cavity leading up to the dump core experienced vacuum leaks. As a result of this, it was detached from the beam line and was disconnected from the vacuum system [5].

The obsolescence of the dump as well as the limitations induced by the reduced cooling performances after these events forced the design, construction and installation of a new generation dump, capable of coping with the requirements of the LIU Project.

![Figure 1: Technical drawing of the previous PSB dump core. Dimensions are reported in mm.](image)
1.2 Dump Area Layout

The PSB external dump is located at the end of the BTM line, after the PSB extraction line and below the transfer line feeding the ISOLDE facility (see Figure 2). As it can be seen in Figure 3, the old dump core was located inside a 5 m-deep, 1 m-diameter cavity shielded by hollow-cylinder shaped concrete blocks.

Due to limitations on the possible interventions in the PSB extraction area, the new dump core had to be installed in the same cavity as the old one [5]. The compatibility with the installation inside the cavity was, therefore, one of the main factors that drove the design phase for the new dump core and its shielding.

![Figure 2: Layout of the Proton Synchrotron Booster (PSB). The PSB dump is located at the end of the BTM line, below the transfer line to ISOLDE.](image)

2 Beam Parameters

Based on past experience [6], around 6% of the beams extracted from the PSB are regularly dumped during normal operation. Considering conservatively 10% of the extracted protons to be dumped, as well as the increase of the intensity due to the installation of the Linac4, around $5 \times 10^{19}$ protons will reach the dump core each year.

Moreover, in the case of commissioning periods, up to 50% of the beams that are extracted from the PSB are sent to the dump for several consecutive months. This is the case, for example of the commissioning period that is foreseen after the connection of the Linac4 to the PSB and the consequent upgrade to 2 GeV beam energy.
Figure 3: Layout of the PSB Dump area. On the left of the picture, the end of the BTM line and the BTY line towards ISOLDE. On the right, the old dump core, its shielding and beam pipe inserted in the dump cavity.

Out of all the possible beams extracted from the PSB, the most demanding conditions for the dump would arise with the beam whose main parameters are listed in Table 1. Under these conditions, the beam dump was designed to have a lifetime of 25 to 30 years, excluding any further upgrade of the accelerators.

Table 1: Parameters of the most critical beam (NORMGPS) for the operation of the dump, after LS2 [6].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max beam intensity</td>
<td>$1 \times 10^{14}$ particles/pulse</td>
</tr>
<tr>
<td>Beam energy</td>
<td>2 GeV</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.94 µs</td>
</tr>
<tr>
<td>Pulse period</td>
<td>1.2 s</td>
</tr>
<tr>
<td>Max. dump rate</td>
<td>50 %</td>
</tr>
<tr>
<td>Average beam current</td>
<td>13 µA</td>
</tr>
<tr>
<td>Average beam power</td>
<td>13.3 kW</td>
</tr>
<tr>
<td>Beam size ($1\sigma$, H × V)</td>
<td>13 mm × 13 mm</td>
</tr>
</tbody>
</table>

3 Design of the New Dump

3.1 Dump Core Design

As already mentioned in section 1.2, the only possible location for the installation of the new dump was the same dump cavity at the end of the BTM line where the old dump was installed. Given these physical constraints, the structure of the new core-shielding assembly is similar to the old one. It once again consists of a cylindrical dump core installed at the downstream end of the dump cavity and surrounded by a set of cylindrical shielding blocks. The materials, cooling technology and dimensions of the new core are, however, different from the old one.
As described in Sec. 1.1, the previous core was made up of a series of steel disks, with a total length of 490 mm. Due to the higher energy of the upgraded beam, however, a longer dump made of a higher density material is required in order to contain most of the prompt radiation produced in the beam interaction process. In this sense, copper alloys, thanks to their high density and high thermal conductivity, are ideal candidate materials. Considering a dump entirely made of copper, the nuclear inelastic scattering length ($\lambda$) of 2 GeV protons is 13.8 cm. A dump length of at least 140 cm, corresponding to roughly $10\lambda$, was therefore required to fully contain the impacting beam and reduce the uncollided proton fraction escaping the dump down to less than $5 \times 10^{-5}$.

Since the temperatures and stresses resulting from the energy deposited in the dump by the beam are too high for a long term reliable operation of pure copper (Cu-OFE), a Copper-Chromium-Zirconium (CuCrZr - C18150) alloy was selected. Although the thermal conductivity of this alloy is slightly lower than that of pure copper, it features higher strength at the expected operating temperatures, allowing for both peak temperatures and stresses to be safely maintained within the limits of this material.

The diameter of the dump core was required [6] to contain up to $5\sigma$ of the maximum beam size. According to the estimations of beam size variability reported in [6], the maximum beam size is given for the 1.0 GeV NORMGPS/NORMHRS beam, calculated to measure 185 and 192 mm at $5\sigma$ in the horizontal and vertical plane, respectively.

A CAD model of the new dump core design that resulted from taking into account these requirements is shown in Figure 4. As it can be seen, the length of the core was increased from 490 to 1500 mm. The diameter was also increased from 220 to 400 mm. The lateral surface of the core features a dense series of fins, which, as it will be further detailed in section 3.3, contribute to drastically increase the heat transfer surface of the dump core with its air cooling system.

Due to size constraints imposed by the manufacturer, the dump core was split longitudinally into three cylindrical pieces of equal diameter. These parts were then clamped together by means of threaded rods in order to ensure thermal contact. Two handles were screwed onto the front face of the dump core, to which stainless steel cables were attached so that the dump could be extracted easily in the future.

![Figure 4](image_url): (left) Front and (right) section view of the CAD model of the new CuCrZr PSB dump core. Dimensions are reported in mm.
3.2 Dump Core-Shielding Assembly

The current dump core-shielding assembly is shown in a CAD section view in Figure 5. As described in section 3.1, this assembly was designed to be installed in the same dump cavity that has been used since the installation of the PSB.

Since the new dump diameter is larger than that of the previous one, the space left for shielding blocks is smaller. A higher density material was therefore required. Cast iron has been used for the three downstream shielding blocks, while concrete has been chosen for the two upstream ones (closer to the cavity entrance) in order to minimize the residual dose in the area outside of the cavity. As it can be seen in Figure 5, the five blocks have an annular geometry and cover the whole depth of the cavity. In the radial direction, a gap of 30 mm is left between the inner diameter of the blocks and the tip of the dump core’s fins, so as to contain the extent of the pressure drop experienced by the air flowing in the gap.

![Figure 5: CAD Section view of the current dump core-shielding assembly, showing the CuCrZr dump core, the cast iron shielding blocks as well as the concrete ones. The ducts for the air cooling are also visible as well as the aluminum beam pipe.](image)

As it is shown in Figure 6, each shielding block features two series of skates. The lower skates allow the blocks to slide onto a pre-existing steel rail, which is fixed onto the external concrete shielding of the dump cavity. The upper skates, in turn, allow the dump core to reach its position at the downstream end of the cavity by sliding on the shielding blocks, once these have already been inserted.

With the current configuration of the beamline, beams sent to the dump travel in air for approximately five metres. In order to minimize the radiological impact of this design, the air activated by the beam is confined in an aluminum air pipe over almost this total length.
3.3 Dump Cooling

After the upgrade to 2 GeV beam energy, during prolonged phases of full intensity beam dumping, the power that will have to be extracted by the cooling system will amount to 10.7 kW. This is the result of the sum of the energy deposited by the beam in the dump core and its shielding, averaged over the repetition rate of 2.4 s. As it is further detailed in section 4.1, this energy deposition is evaluated by means of simulations performed using the FLUKA[7] Monte Carlo code.

In order to dissipate this amount of power, either water or air would have been viable solutions for the cooling system. Considering the radiation protection challenges associated to the use of water, such as the higher production (and retention) of tritium and the danger posed by water leaks, air was chosen as the coolant for this specific application.

As it was the case for the first generation dump, it was not required for the new dump core to operate in vacuum. This greatly simplified the design of the cooling system (schematics shown in Figure 7). As it can be seen, air is blown from the downstream end of the dump through two inlet ducts that are housed in the lower part of the shielding blocks (which are also visible in Figure 6). Once it reaches the end of the cavity, the air is then forced to flow backwards between the fins placed along the lateral surface of the dump. Finally, the air flows out of the cavity into the tunnel, where it is removed by the existing tunnel ventilation [8].

As it can be seen in Figure 8, the air handling unit (AHU) is located outside of the cavity in a low-irradiation beam area, beside the beam line. It is composed of two independent fans in order to provide redundant operation in case of failure of one unit [8].

The air supply is taken from the general ventilation system of the area, which has a maximum
temperature of 20 °C. The required flow rate is 1800 Nm\(^3\)/h, in order to maintain the dump core within the specified temperatures and to keep the air temperature increment below 20 °C. The cooling parameters are summarized in table 2.

**Figure 7**: Scheme of the cooling system of the new PSB dump.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to be extracted</td>
<td>10.7 kW(^a)</td>
</tr>
<tr>
<td>Cooling system type</td>
<td>Forced air</td>
</tr>
<tr>
<td>Coolant working temperature (inlet)</td>
<td>20 °C</td>
</tr>
<tr>
<td>Nominal coolant flow</td>
<td>1800 m(^3)/h</td>
</tr>
<tr>
<td>Coolant temperature increase (estimate for the entire circuit)</td>
<td>17 °C</td>
</tr>
</tbody>
</table>

\(^a\) The power to be extracted is the sum of the power deposited in the dump core (9.4 kW) and in the shielding (1.3 kW)

### 4 Finite Element Analyses

Both CFD and thermo-mechanical analyses were carried out using the energy deposition maps obtained from the FLUKA\([7]\) Monte Carlo simulations as input to evaluate the heat transfer between the dump and the surrounding air.

#### 4.1 Energy deposition

In order to determine the energy density distribution within the dump, simulations were performed using the FLUKA Monte Carlo code \([7]\). Figure 9 shows the distribution of energy density deposited inside a CuCrZr cylinder of 400 mm diameter and 2 m length, resulting from the interaction
Figure 8: AHU and air cooling ducts under the staircase; beam dump cavity on the right; BTM and BTY beam-lines in the foreground.

with the 2 GeV proton beam as described in the "beam parameters" section. The figure displays the top half of a longitudinal section of the cylinder.

As expected, a larger energy density is present in close proximity of the upstream face of the dump. For this reason, a high thermal conductivity material is required, so that this heat can be efficiently evacuated from the outer surfaces of the block.

Based on these simulations, it was decided to use a length of 1.5 m and a diameter of 470 mm for the dump.

Figure 9: Energy density inside dump induced by the proton interaction on CuCrZr (GeV/cm³/pulse).
4.2 Calculations on Air

Different CFD simulations were performed to determine the behavior of air in the circuit and to improve the design to optimize the heat transfer between the dump and the surrounding air. FLUENT and ANSYS® CFX were used.

Considering the space constraints, it was found that the best performance was obtained with the addition of fins as described in section 3.3.

The pressure drop in the entire system is of the order of 500 Pa and the air temperature was calculated to increase from 20 °C (maximum inlet temperature) to 33 °C at the exit of the cavity.

4.3 Thermo-mechanical calculations

The results obtained from the CFD simulations were imported into a thermo-mechanical model in ANSYS in the form of a boundary condition around the dump. In this way the distribution of heat transfer coefficient and air temperature at the dump-air interface is fully integrated in the thermal model. The maximum temperature at steady state, including the peak generated by each pulse reaches 150 °C. The temperature distribution inside the dump, at steady state conditions and for the highest power beam, is shown in Figure 10. Once a pulse impacts the dump, there would be a further increase of the peak temperature of the order of a few degrees.

![Figure 10: Temperature distribution in the PSB dump at steady state.](image)

This temperature profile generates a heterogeneous thermal expansion in the material that induces stresses.

Figure 11 shows the minimum principal (compressive) stress distribution inside the dump at steady state.

Additionally, peaks of 60 MPa are produced by the dynamic effect of each pulse hitting the dump, resulting in a total stress of around 100 MPa. It should be noted that the dynamic loading plays an important role as the pulse period could be as short as 2.4 s over several hours (especially during commissioning). In other words, the loading could reach over 1 million cycles in one month only.
Physical and mechanical properties of CuCrZr depend on temper state and on testing temperature [9–11]. This alloy is precipitation hardened and can obtain final mechanical properties by solution annealing followed by cold working and ageing. Yield strength decreases with temperature and this dependency was taken into account in the material model of the finite element analyses. The allowable stress for a solution annealed and aged temper is generally above 200 MPa for temperatures up to 150 °C, i.e. well above the stresses calculated in this study.

Nevertheless, since core hardenability depends on the diameter of the semi-finished product from which the dump was machined, the actual mechanical properties in relevant positions were experimentally measured on samples extracted from a part of the same dimensions specifically produced for this purpose (manufactured together with the parts actually used for the dump core). The results from these tests are summarized in Figure 12 and show that at room temperature the material is fulfilling the minimum requirements ($R_{p0.2} = 270$ MPa, $R_m = 360$ MPa and $A = 15.0\%$).

![Figure 11: Compressive stress distribution in the PSB dump at steady state.](image1)

![Figure 12: Mechanical properties obtained from tensile tests on samples extracted from parts that were identical to those for the dump core [12].](image2)
Even though the above comparison suggests that the design constraints could be relaxed as the material could accept higher stresses and temperature, it should be noted that the dynamic loading conditions produced by the pulsed beam has an important effect on the fatigue life of the material.

5 Replacement of the original dump

5.1 Radiation protection considerations

As shown by the dose rate measurements that are summarized in Table 3, due to 40 years of irradiation, the dose rate of the old dump core was particularly high. As a consequence of this, the dismantling procedure was defined following the ALARA (i.e. "As Low As Reasonably Achievable") [13] safety principle. This approach strives for the minimization of the dose of radiation to personnel by employing all reasonable methods.

For the case of the PSB dump, the application of the ALARA approach started with the creation of a map of the dose rate in the area where the works would be performed. On the basis of this, as well as of a detailed list of the actions to be taken and the time required for each of them, a work and dose planning document was elaborated. This document contained a planning of the activities to be executed by each worker and the respective estimated absorbed dose. The workers also had to be trained for the tasks they performed and the dose absorbed by each of them was continuously monitored.

Table 3: Results of the dose rate measurements [µSv/h] performed on the main components of the old dump core-shielding assembly as they were being extracted from the cavity [14].

<table>
<thead>
<tr>
<th>Object</th>
<th>Dose [µSv/h]</th>
<th>Distance [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dump core + beam pipe assembly</td>
<td>1100</td>
<td>160</td>
</tr>
<tr>
<td>Beam pipe</td>
<td>35</td>
<td>160</td>
</tr>
<tr>
<td>Shielding container of dump core and beam pipe</td>
<td>750</td>
<td>Contact</td>
</tr>
<tr>
<td>Innermost shielding block</td>
<td>2500</td>
<td>10</td>
</tr>
<tr>
<td>Outermost shielding block</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

5.2 Removal and dismantling of the old dump

5.2.1 Preparatory steps

The removal and dismantling of the old dump first required three preparatory steps:

1. Pre-shielding. In this phase, a steel cylinder, visible in Figure 13, was inserted in the beam pipe in order to reduce the radiation from the dump core out of the cavity. In this way, the dose received by the workers during the following activities could be reduced from 120 µSv/h down to 15 µSv/h. This step was carried out in April 2013, four months prior to the following operations, and also proved useful for other activities in the area, prior to the removal of the dump;

2. Temporary dismantling of the equipment in the BTM and BTY lines. In order to have the necessary space for extracting the old dump core-shielding assembly, the equipment in the
BTM and BTY lines leading up to the dump cavity had to be temporarily dismantled and stored in a different facility;

3. Lining of the area outside the dump with a plastic film. This coating, resistant to the mechanical stresses expected during the following dismantling activities, was used to reduce the risk of contamination from the existing surface contamination of the area.

5.2.2 Extraction and handling of the dump core and beam pipe

**Figure 13**: a) Stainless steel radiation plug b) In green, insertion of the radiation plug at the end of the beam pipe of the old dump core-shielding assembly. The dashed lines indicate the position of the cuts performed by the saw.

**Figure 14**: Tooling for the extraction of the dump core and beam pipe.
Once the preparatory steps were carried out, the necessary tooling for the extraction of the dump core was installed outside the cavity, as shown in Figure 14.

The extremity of the beam pipe was attached to a winch by means of a clamping tool. Then, as shown in Ref. 15, by operating the winch, the dump core and the beam pipe were slid out of the cavity onto a support structure with rollers. After the full extraction of the assembly, a total of four cuts, indicated in Figure 13 with dashed lines, were performed on the beam pipe by means of a remotely-operated saw. After each cut, the assembly was pushed back towards the cavity, thereby making each cut part gradually fall into a lead-shielded container, visible in Figure 14.

After the cutting procedure was completed, the shielded container was transported to the radioactive waste storage facility at CERN for storage and the tooling for the extraction of the old dump core and beam pipe was disassembled.

5.2.3 Extraction of the old shielding blocks

The five shielding blocks were extracted by means of the tooling that is shown in Figure 16. As it can be seen, each shielding block was clamped from the inside by means of a clamping tool that was attached to the same winch cable that was used for the extraction of the dump core and beam pipe. Then, by operating the winch, the blocks were slid out of the cavity and onto a support cradle that was mounted co-axially with the cavity hole. This support cradle featured an extension of the steel rail on which the blocks were resting on the cavity (which can also be seen in Figure 6).

Once fully extracted, each block was loaded by means of a gantry crane inside individual shielded containers for transport and storage in a radioactive waste facility.

5.3 Installation of the new dump core-shielding assembly

Prior to the installation of the new dump core-shielding assembly in October 2013, the dump cavity was inspected and decontaminated. After this, samples of concrete were extracted from the lower
Figure 16: Extraction of one of the old shielding blocks.

Figure 17: a) New CuCrZr dump core prior to its insertion in the cavity. A part of the instrumentation that was installed on the dump core and its cabling is visible on the front face of the dump core and its side. A Pt100 sensor and a thermocouple were installed in each of the highlighted positions. Six more positions on the sides of the dump were the same sensors were installed are not visible in the picture. b) The new CuCrZr dump core fully inserted in the dump cavity.

part of the cavity. This, together with a structural analysis of the previously installed steel rail [15], was necessary to confirm that the dump cavity was indeed able to withstand the increased weight of the new dump core-shielding assembly, which is more than 50% higher than before. The installation then started with the pre-assembly of the air ducts for the ventilation and of the shielding
blocks. This assembly was then progressively slid into the cavity by mounting each block on the same support cradle system that was previously used for the extraction of the old shielding. Finally, as it can be seen in Figure 17, the new dump core was slid to the end of the cavity by sliding it on the rollers embedded in the design of the new shielding blocks.

6 Monitoring and operational feedback

As shown in Figure 17a, a PT100 probe and a thermocouple were installed on each of 12 points on the dump core in order to assess its temperature during operation. Six further PT100 sensors outlet temperature of the air, while a calorimetric sensor gathers data on the flow and temperature of the air between ventilation station and the dump. The data is collected in CERN’s TIMBER logging system [16].

The dump currently operates far below its design parameters (9.4 kW). For example, on 25 July 2018, which is so far one of the days when most power has been deposited in the dump, only 0.964 kW were dumped in the PSB (the beam energy was still 1.4 GeV). This power produced a temperature increase of 1.3 °C in the air coolant, from 30.8 °C (inlet temperature) to 32.1 °C (outlet temperature).

7 Conclusions

In order to cope with the more intense and powerful beam expected after the PS Booster upgrade during LS2, thorough calculations were performed to produce a robust, conservative (hence reliable) beam dump design. In 2013 the new dump was installed in the same cavity as the old dump in 2013, following strict radio-protection protocols to minimize the dose to personnel. The new dump consists of three cylindrical blocks of CuCrZr, held together by screws and spring washers. The assembly is cooled by forced air convection, injected into the cavity where the dump is located and flushed back out into the accelerator tunnel. To maximize the cooling, fins were included in the design. Currently, the dump operates well below its design parameters and is ready to handle the increased load expected after 2021.

8 Acknowledgment

The LIU-PSB project team at CERN has given a significant contribution to develop, support, review and improve this design. Special thanks to the following groups at CERN: EN-STI, EN-MME, EN-CV, EN-HE, BE-OP.
References


