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Report

Design of Air-Cooled Beam Dump for Extraction Line of PS Booster

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Abstract

A new beam dump has been designed, which withstands the future proton beam extracted from the Proton Syncrotron Booster (PSB) at CERN, consisting of up to 1E14 protons per pulse at 2 GeV after its upgrade in 2018/2019.
In order to be able to efficiently release the deposited heat, the new dump will be made out of a single cylindrical block of a copper alloy and cooled by forced ventilation.
In order to determine the energy density distribution deposited by the beam in the dump, Monte Carlo simulations were performed using FLUKA, and thermomechanical analyses carried out by importing the energy density into Ansys. In addition, CFD simulations of the airflow were carried out in order to accurately estimate the heat transfer convection coefficient on the surface of the dump.
This paper describes the design process and highlights the constraints of integrating a new dump for increased beam power into the existing facility.

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INTRODUCTION

The current dump located at the extraction of the PSB was installed during its construction, which was completed in 1972. The PSB has undergone several energy upgrades since then, from 800 MeV (which was the design energy) through 1 GeV up to its current extraction energy of 1.4 GeV. Since the dump was designed for the initial energy, it is no longer adapted for the current running conditions. In view of the 2 GeV upgrade and the intensity increase that will be possible with the future connection of Linac4 to the PSB, the dump needs to be upgraded so that it can properly absorb the future beam. The dump replacement is scheduled for autumn 2013, in order to profit for the long shutdown of all CERN accelerators (LS1) taking place during 2013-2014. The aim of this study is to propose a new design that can cope with the future beam parameters, taking into consideration the radiological requirements as well as the physical, infrastructural and budgetary constraints inherent of the project.

Dump Area Layout

The current dump and five cylindrical shielding blocks are located inside a 5m-deep, 1m-diameter horizontal cavity, as shown in Fig. 1.

The new dump and shielding blocks must be installed in the same location; hence, the dimensions of the assembly are limited by this cavity.

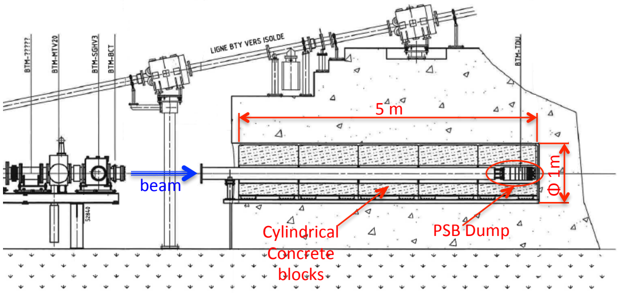

Figure 1: Dump area layout.

BEAM PARAMETERS

Beams of different characteristics will be sent to the dump at rates that could range between 6 % ("normal" beam operation) and 50 % of the pulses circulating in the booster [1]. The latter is an extreme case that will be expected only during commissioning of the upgraded booster. However, since this commissioning period could last several months, the dump was designed to sustain this regime.

Out of all possible scenarios, the most demanding conditions for the dump would occur with the beam parameters listed in table 1.

Table 1: Beam parameters used for design

Parameter	**Value**
Max beam intensity	1E14 particles/pulse
Beam energy	2 GeV
Pulse length	0.94 ms
Pulse period	1.2 s
Max dump rate	50 %
Average beam power	13.33 kW
Average power to dump	9.43 kW
Minimum beam size (1σ, H x V)	13 mm x 13 mm

PROPOSED DESIGN

Given the physical constraints, the main layout of the new dump-shielding assembly is similar to the current one, i.e. a cylindrical dump installed at the downstream end inside a set of cylindrical shielding blocks. Nevertheless, the materials and dimensions of the new design are different for the old one.

Materials

The current dump is made up of an array of carbon steel disks, with a total length of 50 cm. For the new dump, a material with higher density and thermal conductivity is required as both beam energy and thermal power to be evacuated by the dump are significantly higher than those of the current dump.

The material that best fulfills the above requirements was copper [2,3,4]. Nevertheless, since the temperatures and stresses generated by the energy deposition in the dump are too high for long term, reliable operation in pure copper, a Copper Chromium Zirconium (CuCrZr) alloy was selected. Although the thermal conductivity of this alloy is lower than that of pure copper, it features higher strength at the operating temperature and its thermal conductivity is still excellent, which allows for peak temperatures and temperature gradients (hence stresses) to be maintained within the limits of this material.

Since the new dump diameter is greater than the current one, the space left for shielding blocks is smaller; thus a higher density material is also required for them. Carbon steel or cast iron is proposed for the three downstream shielding blocks. For the two upstream blocks (closer to the cavity entrance), concrete was chosen in order to minimize the activation in the area outside of the cavity.

Energy deposition

In order to determine the energy density distribution within the dump, Monte Carlo simulations were done using FLUKA [5]. Fig. 2 shows the distribution of energy inside a CuCrZr cylinder of 400 mm diameter and 2 m length, resulting from the interaction 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, there is a high concentration of energy near the center of the upstream face of the dump. For this reason, a high thermal conductivity is required, so that this heat can be more easily evacuated from the outer surfaces of the block.

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

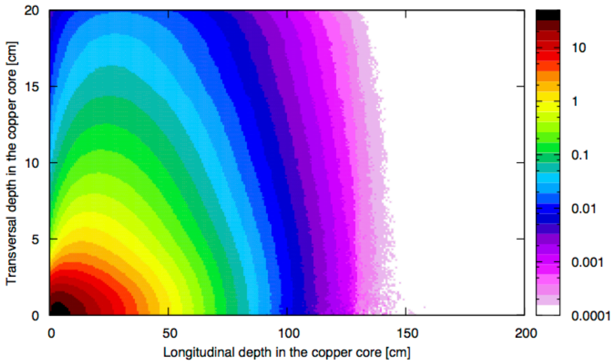

Figure 2: Energy deposition inside dump (GeV/cm^3)

Cooling

Considering the high production of tritium that would result from the use of a water circuit in direct contact with this dump, it was decided to use air as coolant, as shown in Fig. 3.

Air is blown to the downstream end of the dump through two ducts located on the lower part of the assembly. This air is then forced to flow along the lateral surfaces of the dump and out of the cavity.

The supply air is taken from the general ventilation system of the area, which has a temperature of 20 °C in the worst case (normal range being 12−18 °C).

The flow rate required is 1800 m^3/h, in order to maintain the dump within acceptable temperatures and to keep the air temperature increment below 20 °C.

FINITE ELEMENT ANALYSES

Both CFD and thermo-mechanical analyses were carried out using the energy deposition maps obtained from the FLUKA simulations as input to evaluate the heat transfer between the dump and the surrounding air.

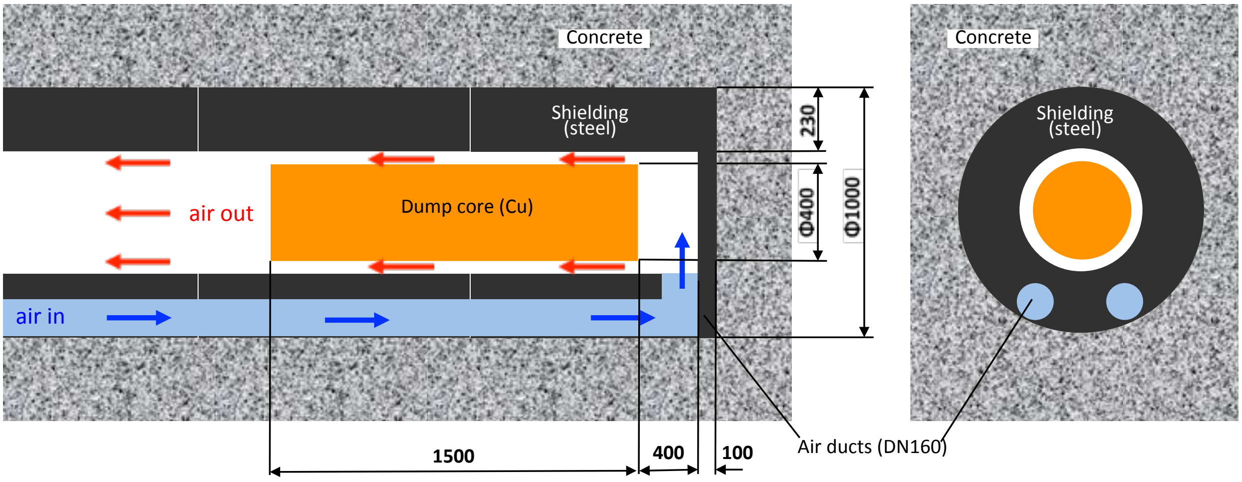

Figure 3: Proposed design for new dump-shielding assembly

Calculations on Air

Different CFD simulations were performed to calculate 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 CFX-Ansys were used.

Considering the space constraints, it was found that the best performance was obtained with the addition of fins around the cylinder, parallel to the beam axis. The fin geometry proposed is 35 mm high x 5 mm thick, with a pitch of 15 mm (10 mm of space between two fins). In this way, the heat transfer surface is increased by more than a factor of 5, with respect to a cylinder without fins.

The pressure drop in the entire system is of the order of 500 Pa and the air temperature increases from 20 ^{o}C (inlet temperature) to 33 ^{o}C at the exit of the cavity.

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 air temperature at the dump-air interface is fully integrated in the thermal FE model.

The maximum temperature at steady state, including the peak generated by each pulse reaches 150 ^{o}C

The temperature distribution inside the dump is shown in Fig. 4 (no effect of single pulse included in the figure).

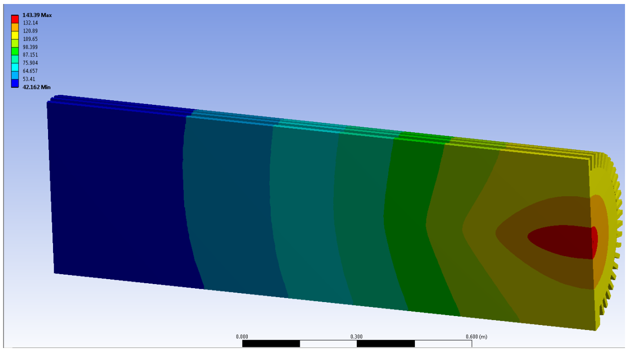

Figure 4: Temperature distribution at steady state.

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

Fig. 5 shows the compressive (minimum principal) stress distribution inside the dump at steady state.

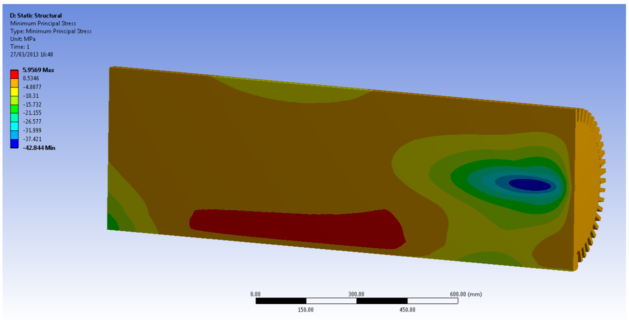

Figure 5: Compressive stress distribution at steady state.

Additionally, peaks of 60 MPa are produced by the dynamic effect of each pulse hitting the dump, resulting in a total stress of 100 MPa. It should be noted that the dynamic loading plays an important role as the pulse period could be as high as 2.4s over several days (especially during commissioning). In other words, the loading could reach a 1E6 cycles over one month only.

Physical and mechanical properties of CuCrZr depend on temper state and on testing temperature [2,3,4]. This alloy is precipitation hardenable 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 FE 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 will be machined, actual mechanical properties in relevant positions shall be experimentally checked on a component specially fabricated of representative dimensions.

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. Moreover, the mechanical properties can be degraded by the effect of a long exposure at temperature due to the long time of operation of the dump (25-30 years).

CONCLUSIONS

In order to cope with the more intense and powerful beam expected after the PS Booster upgrade, thorough calculations were performed to produce a robust, conservative (hence reliable) beam dump design.

AKNOWLEDGMENT

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