ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMG001

ENGINEERING DESIGN AND PROTOTYPING OF THE NEW LIU PS INTERNAL BEAM DUMPS

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Abstract

For the LHC Injectors Upgrade (LIU) at CERN, the two Proton Synchrotron (PS) internal dumps are being redesigned and upgraded to cope with the future high intensity beams. The dumps are installed as active elements in the lattice, in straight sections between the main bending magnets. The dumps are moved into the beam when requested by operation, and shave the circulating beam turn-by-turn stopping the beam after about 6 ms. The shaving induces a very localized beam energy deposition on the dump surface in a thickness of tens of microns.

This paper presents the new dump design, focusing on the active part (dump core design and interaction with the beam) and describing its operational constraints, such as dumping the beam 200 000 times per year for 20 years, intercepting close to 100 kJ beams, and reaching the beam trajectory in 150 ms. For the dump design, the fast maintenance due to high residual dose rate is also considered. These constraints have a major impact on the technological choices.

INTRODUCTION

In the framework of LIU project [1], the two present PS internal dumps, installed in the PS machine in 1975, are being redesigned and upgraded to withstand the higher intensity beams which will be available after LIU [2]. The internal dumps are used during beam operation (in manual and automatic mode) for studying new beams, solving problems with the machine or preventing beam extraction from the PS if required. Due to space limitations in the machine, the dumps are not sufficiently long to fully absorb the proton beam and so they act in reality more as beam diluters.

After several design iterations [3], the new dumps have been designed with a dump core made of graphite and CuCr1Zr alloy. Water circuits, bonded with diffusion bonding by Hot Isostatic Pressing (HIP) technique [4], are cooling the core in ultra-high vacuum dissipating the heat deposited by the beam. The core of the dumps is interacting with the circulating beam and it is moved by a spring-based actuation mechanism (see Fig. 1). The time needed by the dump to enter the beam area is around five orders of magnitude longer than the revolution time of the beam in the PS ring. Therefore, a multi-turn dumping phenomenon occurs: the dump shaves the beam while moving across the beam vacuum chamber. Turn-by-turn the dump intercepts a small fraction of the proton beam. This operational behaviour has driven the design of the actuation mechanism, the dump core, as well as the material selection. A new approach has been developed with FLUKA to simulate the beam shaving, coupled with ANSYS® to define a new dump core design [5].

The two new dumps shall be installed in the PS ring during the Long Shutdown 2 (LS2) planned to last from January 2019 until May 2020 for the PS machine. The proposed new dump design is currently being prototyped to validate the design choices, components and simulations.

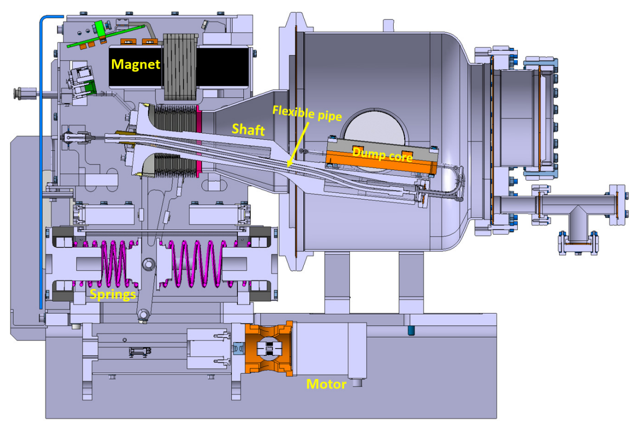

Figure 1: 3D model of PS dump prototype with mechanism in parking position.

DUMP CORE

The new dump core is a $180 \times 230 \times 40\,\mathrm{mm}^3$ block made of two materials with a total mass of 12.5 kg (see Fig. 2). Reducing the core mass is a key aspect to increase the velocity of the actuation system moving the dump. The first material is isostatically pressed graphite. The second material is a copper alloy, the CuCr1Zr. The beam first interacts with the graphite losing a fraction of its energy. The CuCr1Zr catches a part of the secondary particles showers generated by proton beam impact on graphite. Three parallel 304L stainless steel cooling pipes are cooling the dump core and are linked to the flexible pipes inside the dump shaft. CuCr1Zr and the pipes are thermally linked together, via a diffusion bonded interface generated by means of Hot Isostatic Pressing (HIP) process.

The graphite to CuCr1Zr thermal interface is granted by mechanical contact: the graphite is screwed to the CuCr1Zr bottom plate by stainless steel bars on the sides and CuCr1Zr

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bars in the center. The front edge of the graphite block is rounded to spread the beam impact on a larger area. In addition, in order to prevent any direct beam impact on CuCr1Zr, the dump core is tilted by one degree with respect to the beam direction. The graphite is always firstly impacted by the beam protecting the CuCr1Zr that would be damaged otherwise. Finally, slits are proposed to be machined in the CuCr1Zr part to act as stress relievers decreasing the stresses in this material.

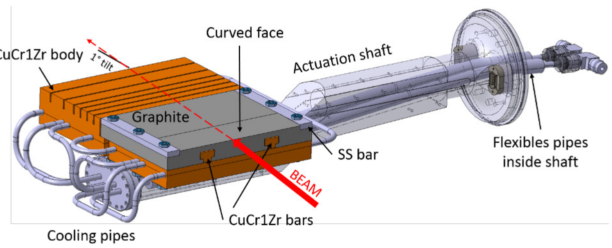

Figure 2: Dump core design.

Thermo-Mechanical Simulations

The thermo-mechanical response of the core to the beam shaving is simulated with ANSYS® Mechanical (Workbench). A transient thermal simulation one-way coupled with a transient structural simulation is performed. The heat generated by the impacting protons is obtained as an input from FLUKA simulations [5]. The beam is assumed to impact in the horizontal center of the core and therefore only half of the geometry is modeled and a symmetry condition is applied.

The selected beam for the core design is the nominal HL-LHC 25ns combining high intensity (2.4×10^{13} protons) with a small beam spot size of 1.74 mm × 0.87 mm (horizontal × vertical) [2]. The dumping process is simulated at the top momentum of 26 GeV/c.

During the beam shaving (lasting approximately 6 ms) a maximum temperature of 1400 °C is reached in graphite and 63 °C in CuCr1Zr (see Fig. 3). A very high but localized temperature region is observed on the graphite surface, where the beam initially impacts the core. 7 kJ (7.3% of the beam energy) is absorbed by the dump core. The rest escapes the core assembly and is absorbed by the dump shielding and by downstream accelerator equipment.

The temperature increase generates bi-axial compression on the graphite surface plane (XZ plane, see Fig. 4). The stress is localized in a small area in the order of a few millimeters and it decreases fast below the surface (see Fig. 5). The stresses in both planar directions (X and Z) are equal in magnitude (−127 MPa), while the stress in the depth direction (Y) is zero, as the surface is a free. The maximum von Mises stress in the CuCr1Zr reaches 33 MPa, which is comfortable with respect to the yield strength (measured to be ~280 MPa at room temperature).

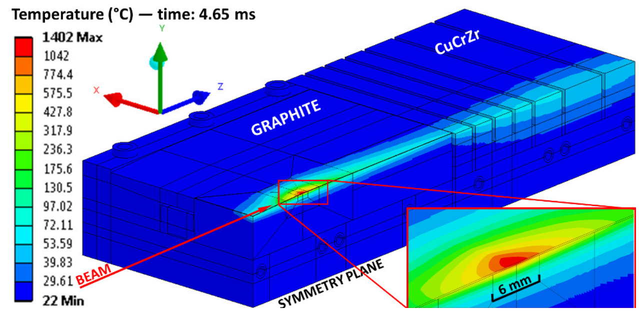

Figure 3: Simulated temperature in the core during the dumping of a single HL-LHC beam pulse.

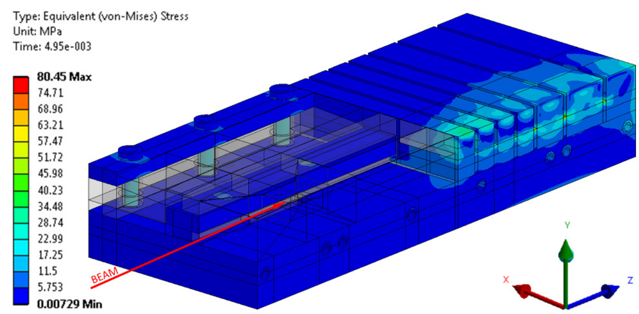

Figure 4: Simulated von Mises stress in the CuCr1Zr during the dumping of a single HL-LHC beam pulse.

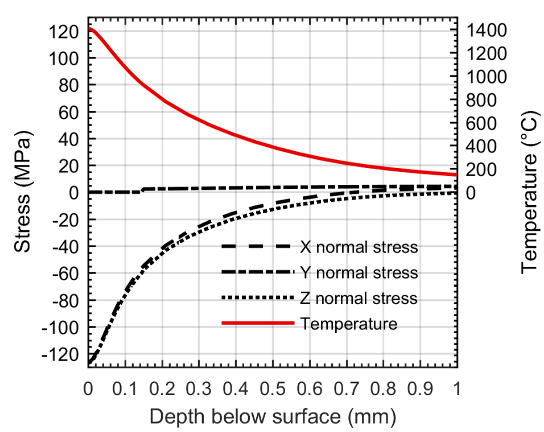

Figure 5: Temperature and stress path below critical location on the graphite surface at 4.65 ms.

Manufacturing Process

The HIP process is a simultaneous application of high pressure and high temperature on the components inside an inert gas atmosphere. The CuCr1Zr core blocks are surrounded by a stainless steel capsule with evacuation tubes to establish vacuum (see Fig. 6) since air should be removed from the interfaces to be bonded. The inert gas is heated up and pressurized in order to apply on the dump core capsule a uniform "isostatic" pressure. This causes the materials to become plastic and the voids in the interface between the CuCr1Zr and the stainless steel collapse allowing diffusion bonding. A perfect thermal bonding (diffusion bonding) is obtained between the tubes and the CuCr1Zr, leading to

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a better thermal performance respect to other assembling techniques like brazing or clamping.

After HIP, a final thermal treatment of the dump core is required to re-obtain the thermal and mechanical properties of the CuCr1Zr lost during the HIP process. It consists in a precipitation hardening followed by a fast quenching in water and an ageing.

During the HIP process and the subsequent thermal treatment, the oxidation of the tubes surfaces should be avoided, especially the internal ones, since the thermal conductivity can be locally decreased. For this reason, during HIP, the tube inner part are protected by steel wool (see Fig. 7). During the thermal treatment, the inner part of the tubes is protected while performing vacuum and sealing the tubes.

The first prototype of the HIP PS dump core has been produced, characterization tests as well as further machining tests are on-going. Destructive tests, aiming at checking the diffusion bonding interface, together with thermal tests and water pressure tests, are part of the dump HIP core qualification phase.

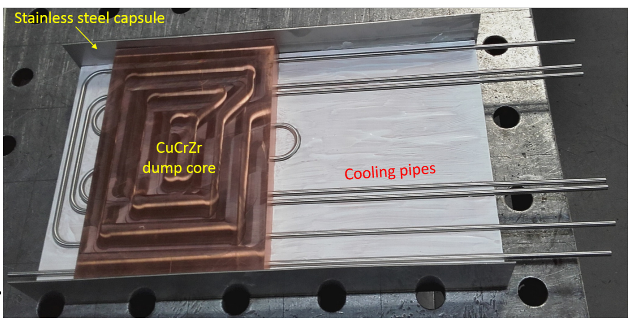

Figure 6: Dump core assembly before HIP.

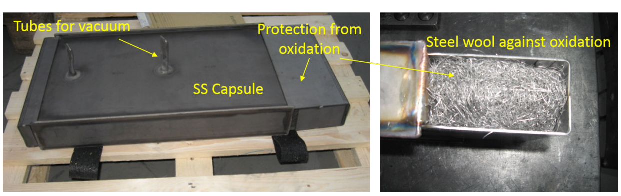

Figure 7: Stainless steel capsule after HIP and protection cage against oxidation.

ACTUATION MECHANISM

The dump core is actuated by a spring and electromagnet-based system with three arms rotating around an axis (see Fig. 1). The dump core is fixed to a shaft located in Ultra High Vacuum (UHV, approximately 10^{-9} mbar) [6]. When the electromagnet is powered, the core is kept in a parking position outside the beam chamber. When the magnet current is cut, the loaded springs allow the system rotation and the core sweeps into the beam trajectory shaving the beam. From the top position, the opposite springs bring the core back to the parking position, where the magnet is powered again. If a problem occurs with the magnet, a motor can be used to drive the system back in the parking position.

Following the requirements of beam operation [2], the angular movement is from -6° to +6° and the oscillation period (300 ms) drives the choice of the springs stiffness as well as the magnet force. The flipping movement can be repeated, for several hours, for every beam cycle in the PS (every 1.2 s). The total amount of dump oscillations is expected to be 200000 times per year for a lifetime of 20 years.

This design is based on the currently installed PS dump mechanism [7], and has been selected among other technologies because of its ability to do the required movement, its very good reliability, its radiation hardness, and the need of nearly no maintenance. A 3D modeling of the dump prototype is done (see Fig. 1) while the mechanism assembly is in production (see Fig. 8).

Figure 8: The mechanism chassis and the rotating spring arm assembly of the dump prototype.

CONCLUSION

Detailed engineering studies and prototyping steps led to an upgraded PS internal dump core and mechanism design.

The design follows the specified requirements in terms of cycle time, lifetime and core material integrity. Thermo-mechanical simulations proved the survival of the core graphite material to the shaving impact for high intensity beams after LIU. The dump core and the mechanism are currently being prototyped to validate the manufacturing processes. Cycling tests are foreseen in atmosphere and under vacuum to validate the commercial components choice, such as the magnet, the springs, the bellow, the bearings, and the vacuum vessel. Steady state thermal tests of the core, using heaters, will benchmark the thermal simulations and will allow checking the cooling performance.

After the prototyping phase, the new dumps will be manufactured and installed during the Long Shutdown 2 of the CERN accelerator complex, in 2020.

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