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ANALYSIS ON THE THERMAL RESPONSE TO BEAM IMPEDANCE HEATING OF THE POST LS2 PROTON SYNCHROTRON BEAM DUMP

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Abstract

The High Luminosity Large Hadron Collider (HL-LHC) and the LHC-Injection Upgrade (LIU) projects at CERN are upgrading the whole CERN accelerators chain to increase beam brightness and intensity. In this scenario, some critical machine components have to be redesigned and rebuilt. Due to the increase in beam intensity, minimizing the electromagnetic interaction between the beam and devices is a crucial design task. Indeed, these interactions could lead to beam instabilities and excessive thermo-mechanical loadings in the device. In this context, this paper presents an example of multi-physics study to investigate the impedance related thermal effects. The analysis is performed on the conceptual design of the new proton synchrotron (PS) internal dump.

INTRODUCTION

In the framework of the project LIU [1], all the LHC injectors chain is being upgraded in order to operate with beams of increased intensity and brightness. This is critical for those accelerator components that have to interact directly with the beam as collimators, scraper, absorbers or dumps. This class of devices is also know with the name of Beam Intecepting Devices (BID). Their functionality can be deeply affected by changes in beam intensity. Thus, if this parameter increases, detailed and careful studies should be done to assess if the BID will continue to work as expected in the new scenario. In case the functionality is compromised, a new BID has to be redesigned and rebuilt.

The intensity of the beams in the Proton Synchrotron (PS) is foreseen to be doubled with respect to the current situation after the long shutdown 2 (LS2), 2019-2020 [1]. In this scenario, the two current internal dumps, which are responsible for stopping the beam if needed or requested, have to be replaced. It has been proven that they cannot cope with the new post LS2 high intensity beams [2]. The design of the new devices, able to absorb and stop the new intense beams, has been recently completed and it is currently in the prototyping phase [3, 4]. The new PSdumps are scheduled to be installed before May 2020. The initial design of the device presented high impedance, i.e. strong electromagnetic interaction between the beam and the device itself. A high impedance can generate beam instabilities and high RF-Heating [5]. An impedance reduction campaign was carried out at CERN [6]. The design of the new PSdump was electromagnetically simulated in order to individuate the reasons of such a high impedance. The design was modified in order to decrease the electromagnetic coupling between the beam and the device. The operations of simulation and design modification were iteratively repeated until the impedance of the PSdump was under the beam instability threshold [7, 8]. This paper, after the presentation of the device geometry and materials, reviews the impedance of the last PSdump design. Subsequently, it focuses on the impedance heating induced by the beam on the device. Finally, it reports the results of a thermal simulation in a pessimistic scenario.

The device geometry is presented in Fig. 1. The main part of the dump is the dump core ($180\times230\times40$ mm^3) [4], made by two blocks of different materials: Copper Cromium Zirconium (CuCr1Zr) and Graphite. They have to stop and absorb the particle beam. Inside the core, a system of cooling pipes in stainless steel is hipped [4, 9] to the CuCr1Zr block. This boosts the efficiency of the heating exchange between the dump core and its cooling pipes, in which water flows at 22 °C. The dump core and the cooling system is mounted on a movable shaft. The extremity of this shaft can rotate moving the core from its rest position to the working position, i.e. the core is put into the beam trajectory so that the beam is completely absorbed (see Fig. 1 right). The core and its shaft are assembled into a vacuum vessel, as shown in Fig. 1 right.

ELECTROMAGNETIC SIMULATIONS

As anticipated, an impedance minimization campaign was carried out for the device and it is presented in [6]. Thus, this section discusses just the impedance results on the last PSdump model with the aim of computing the induced RF-Heating. The impedance of the device was estimated using the commercial software CST studio suite [10]. It is well known and widely used at CERN for electromagnetic simulations [11]. Its Eigenmode solver [12] computes the resonant frequencies (f_{rn}), the Shunt impedances (R_n) and the quality factors (Q_n) of the nth electromagnetic resonant mode in the PSdump. This data can be fitted with a Lorenzian function and summed up in order to obtain $Z(f)$, the device impedance as a function of frequency f:

$$Z(f) = \sum_{n=1}^{n=\infty} \frac{R_n}{1 + jQ_n\left(\frac{f}{f_{rn}} - \frac{f_{rn}}{f}\right)}, \qquad (1)$$

where $j = \sqrt{-1}$. CST Wakefield solver [13] allowed to compute directly the impedance. The impedance obtained from Wakefield and Eigenmode solver was compared as a benchmark and little differences were found. In Fig. 2 the model used for electromagnetic simulation is shown. In table

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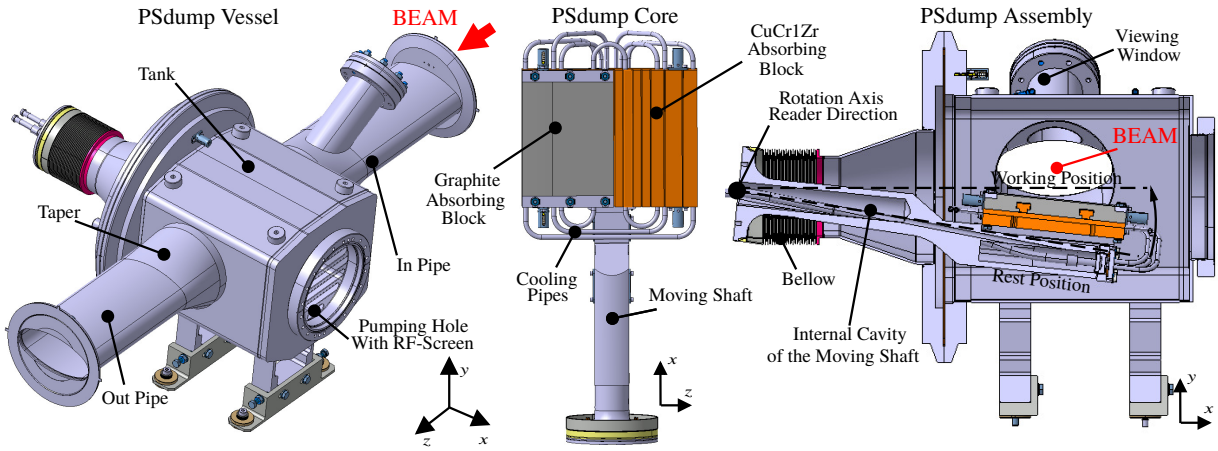

Figure 1: Design of the PSdump with nomenclature. Left: The vacuum vessel, the beam propagation direction is highlighted, note that the beam is propagating along the z axis. Center: The PSdump core, the blocks of Copper Cromium Zirconium (CuCr1Zr) and Graphite that have to abosorb the PS beams. Right: assembly of the core inside the vessel in the rest position. Note that the internal cavity of the moving shaft opens to the environment, thus, this cavity contains air at room temperature.

1 the value of the electrical conductivity for each material has been reported, along with the other considered thermal physical properties. In Fig. 3, the results of the electromagnetic analysis, that is the real part of the impedance obtained with the Eigenmode solver, which is slightly more pessimistic than the one obtained trough the wakefield solver, is reported along with the power spectrum and the normalized beam power spectrum (defined in the next section).

The impedance is characterized by strong resonant modes. This was expected due to the geometry of the device that presents empty volumes. Unfortunately, these volumes are needed for the functionality of the device and cannot be removed.

Table 1: Material Physical Properties at 25 °C

Material	σ_c $\left[\frac{S}{m}\right]$	k $\left[\frac{W}{Km}\right]$	C $\left[\frac{kJ}{Kkg}\right]$	ρ $\left[\frac{kg}{m^3}\right]$
SS 304L	$1.34 \cdot 10^6$	13.3	0.48	7962
Graphite	$1.00 \cdot 10^5$	24.0	0.71	2250
CuCr1Zr	$5.96 \cdot 10^7$	401	0.39	8930

RF-HEATING

Well established results [14] show that the electromagnetic beam-equipment interaction causes a total power deposition proportional to the square of the beam intensity and to the real part of the device impedance according to:

$$\Delta P = \left(f_0 e N_{beam}\right)^2 \sum_{p=-\infty}^{p=+\infty} |\Lambda(p\omega_0)|^2 \, Re\left[Z_{\parallel}(p\omega_0)\right], \quad (2)$$

where N_{beam} is the beam intensity, e is the elementary charge, f_0 is the revolution frequency of the beam in the accelerator, $\omega_0 = 2\pi f_0$, Λ is the normalized beam spectrum, $|\Lambda|^2$ is the normalized beam power spectrum (NBPS)

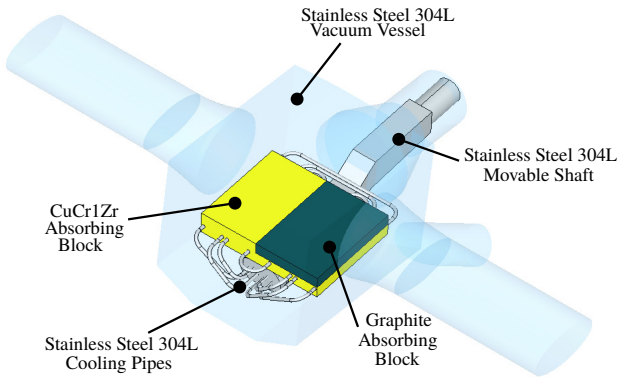

Figure 2: CST model of the new PSdump. The vacuum vessel is represented as transparent.

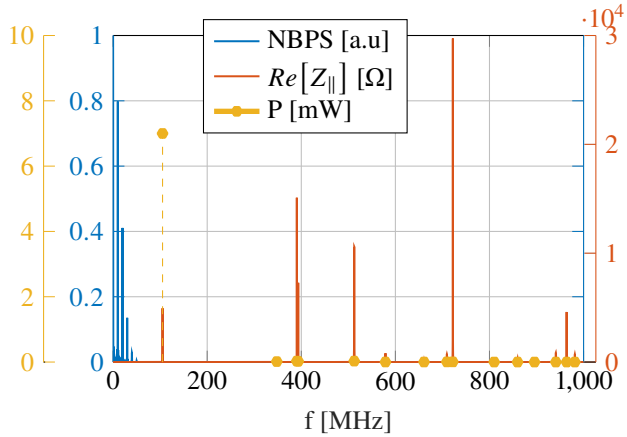

Figure 3: Normalized beam power spectrum [adimensional units] (NBPS), dissipated power spectrum and real part of the impedance. Colors refer to different scales.

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and $Re\left[Z_{\parallel}\right]$ is the real part of the longitudinal coupling impedance.

The beam structure, i.e. bunch length, bunch number and interbunch distance is constantly changing into the PS. To compute the RF-Heating a worst case scenario approach was adopted, i.e. the beam with the larger frequency spectrum which run into the machine for more than 0.5 s was considered among the PS beams. The parameters reported in table 2 represent this scenario. The total beam intensity was set to $N_{beam} = 2.4 \cdot 10^{13}$ protons. In Fig. 3 the NBPS is reported.

Table 2: Bunch parameters selected for the impedance heating calculation, worst case scenario.

Shape	Length (4σ)	Interbunch Distance	γ	N Bunches
gaussian	30 [ns]	100 [ns]	27.74	18

Analysis of the beam dissipated power has also been performed in order to obtain the dissipated power spectrum. A sensitivity analysis technique has been used, i.e. the resonant modes' frequencies have been randomly moved with respect to the initial value obtained by simulations within a range of ±10 MHz to study the coupling between beam spectrum and longitudinal device impedance. The power dissipated by every mode for an average case and for a worst case scenario was computed. In Fig. 3 the worst case scenario is reported. At the frequency values of the first resonant mode, 105 MHz, the NBPS is not totally null and there is a small coupling with the real part of the impedance function, giving a dissipated power of 7 mW. The power dissipated on the other modes can be considered almost negligible.

THERMAL SIMULATIONS

The power dissipated on the device, around 7 mW, seems rather small. However, it has to be taken into account that this power is flowing into the PSdump continuously while the beam is circulating in the accelerator. In specific operational scenarios beams run for several hours in the PS machine uninterruptedly. Thus, this rather small power is applied for a long period of time. Further, it is crucial to know the areas in which this power fluxes into the device. Indeed, if the flux is concentrated in small regions where no cooling system is present, also low values of deposited power could increase appreciably the temperature. This could potentially lead to material outgassing, ablation or even cracking. This last case can happen if the temperature gradient between cold and hot zones is so large to generate intense mechanical stresses. Since a dump is a critical component for an accelerator and because of the reasons listed above, the analysis was carried out with thermal simulations.

The method exposed in [15] was used to obtain the map of the dissipated power on the PSdump. It consists in interfacing two commercial software, CST studio suite and Ansys mechanical [16] in order to compute the thermomechanical effects of the impedance heating.

Every mode below 1 GHz was considered and for each one of them a 3D dissipated power map was obtained. All this contributions were summed up to compute the final power flux, reported in Fig. 4. Only the flux on the core and the shaft has been reported being more than 95% of the total power deposited in the PSdump. Most of the power is deposited in the shaft and in the cooling tubes.

Always considering a worst case scenario approach, a thermal steady state simulation was run. It is implicit in the steady state simulation the assumption that the 7 mW are deposited continuously till the equilibrium is reached. This is a pessimistic scenario because between the extraction of a PS beam and the injection of a new one there is a time interval in which no beam is circulating. Thus, no impedance induced power is deposited in the device.

The only simulated cooling mechanism was the convection on the internal surfaces of the shaft, 5 W/Km^2. The cooling system was ignored. This represents the case of a pump failure. The temperature results are shown in Fig. 5. The maximum temperature increase is clearly negligible being less than 1°C. Thus, no drawbacks are expected.

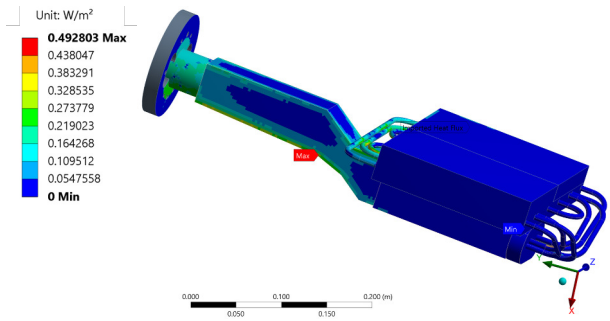

Figure 4: Impedance induced power flux on the core and shaft.

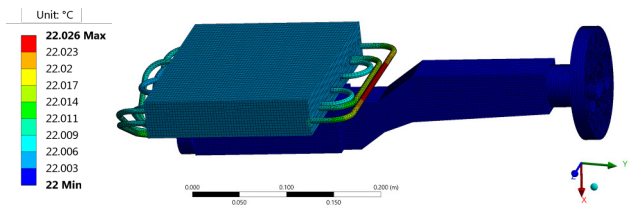

Figure 5: Core and shaft temperature at steady state.

CONCLUSIONS

The paper reports on the analysis done on the impedance heating effects for the new design of the proton synchrotron dump. First, the results of the impedance simulations are discussed, then the computed 3D induced RF-Heating map is presented. Finally, the thermal effects of the impedance heating is estimated in a worst case scenario. The final findings predicts that the RF-Heating does not generate any thermomechanical issue for the presented PSdump design.

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Measurements of the device impedance are foreseen in order to benchmark the electromagnetic simulations.

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