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IMPEDANCE ANALYSIS OF NEW PS INTERNAL DUMP DESIGN

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Abstract

The High-Luminosity Large Hadron Collider (HL-LHC) project at CERN calls for increasing beam intensity in the injector chain. In the Proton Synchrotron (PS), a pre-injector of the LHC, these intensities can result in beam instabilities and potential RF heating of machine components, such that impedance mitigation measures are required. To study these intensity effects, the PS impedance model has been developed and is continuously updated. Each new machine element that is to be added into the accelerator requires an impedance study to minimize its contribution with respect to the machine's overall impedance budget. In such a context, this paper presents the impedance analysis of the new design of the internal beam dump for the PS, showing the design process required to reduce the impedance contribution of this element. Furthermore, the impedance of the currently installed beam dump is analysed in order to compare the impedance contributions of the two designs.

INTRODUCTION

For the installation of near-beam equipment into the circular accelerators at CERN, it is standard procedure to evaluate its contribution to longitudinal and transverse beam impedance, optimise the object, and introduce impedance mitigation measures, if required.

The first and foremost approach for impedance reduction is geometry changes, with the target to reduce or remove resonant modes of the structure. By reducing the volume of the machine element, the resonances within the volume are shifted to higher frequencies where, in most cases, they are expected to have less effect on heating and overall beam stability. Geometrical modifications can be evaluated by reducing the shunt impedance and to suppress resonances that are intrinsic to the geometry, e.g. if the object shape forms an undesired cavity.

Further reduction of resonances can be achieved through the insertion of higher order mode (HOM) couplers. Both impedance reduction approaches are presented here. CST Eigenmode and Wakefield simulations [1] were used to evaluate geometry adjustments and HOM coupler designs.

Currently, two internal beam dumps are installed in the proton synchrotron (PS) at CERN, which will have to be replaced in order to cope with increasing beam intensities. Consequently, a new design was generated by the EN-STI group at CERN [2, 3], which features a larger dump pad. This larger dump pad requires a larger vacuum vessel, which is supporting lower frequency resonances than the current design. As an initial starting design, the dump's vacuum vessel geometry has been reduced in size as much possible.

Electro-magnetically, the new PS dump geometry presents a non-trivial object to have its impedance reduced, as its mechanism consists of a movable, stainless-steel dump arm protruding into the vacuum vessel. This arm is electrically connected to the outer structure and behaves as a resonator stub. Attached to this steel dump arm is the dump pad itself, which is primarily made of copper alloy (CuCrZr) with an additional graphite insert. Due to the proximity of the dump pad and the vacuum vessel walls, we obtain massive capacitive coupling, which requires both above mentioned mitigation measures to suppress the resulting resonances.

These mitigation measures, circular beam pipe tapers and HOM coupling loops, are shown in the final CST model of the dump in Fig. 1 (beam path labeled in red). The movable dump arm is shown in gray (stainless steel), with the dump pad shown in yellow (CuCrZr) and black (graphite). Note that the dump arm is shown in its rest position, i.e., out of the circulating beam path. It should also be noted that the dump pad has a slight incline with respect to the beam trajectory of one degree, as by design.

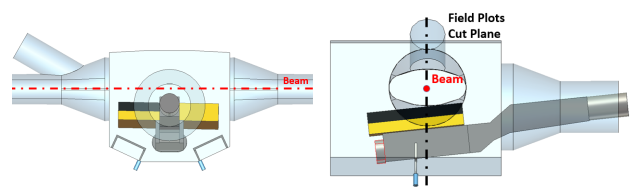

Figure 1: CST model of the PS Dump shown with tapers and HOM couplers (left) with the beam path shown in red. Also shown is the cut plane of the field plots (right).

INITIAL DESIGN

The initial design, with no beam pipe tapers or HOM couplers, was simulated in CST in both Eigenmode and Wakefield solvers, with the results plotted in Fig. 2. These simulation results show good agreement for the frequencies of the modes and shunt impedance (R_{sh}) values, validating our design approach of using the Eigenmode solver to design the tapers and the coupling loops.

Note the major modes at 372, 540 and 722 MHz with shunt impedance values of 44, 28 and 12 kΩ, respectively. All these modes are driven by the strong capacitive coupling from the dump pad to the vessel walls, resulting in high electric fields (E-Field) along the beam path. These three modes have the highest R_{sh} values and are below 1 GHz, making them likely candidates to contribute to longitudinal beam instability. As a result, they are the focus of the impedance reduction measures presented here.

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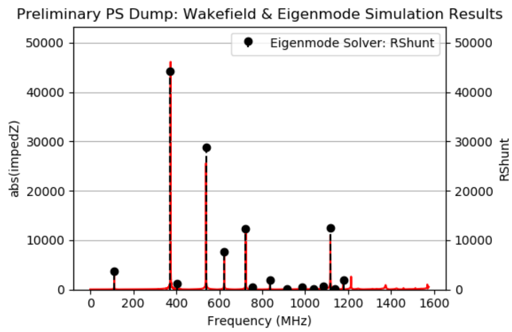

Figure 2: Simulations results in both Eigenmode (R_{sh}) and Wakefield solvers (absolute longitudinal impedance, shown in red) of the preliminary dump design with no tapers or HOM loops.

GEOMETRIC OPTIMIZATIONS

The chamfers on all four corners of the vacuum vessel were free to adjust within reason, both their lengths and angles, but it was found they had nearly no effect on the impedance performance. The remaining geometric free-parameter are the beam pipe to vacuum vessel tapers.

As briefly introduced, the resonance modes involve the dump pad coupling capacitively to the walls of the vacuum vessel at various locations. For the modes with highest shunt impedances, the edges of the dump pad couple capacitively to the conducting walls next to the beam pipe aperture, producing strong E-Fields along the beam line. Thus the initial reduction approach is to modify the geometry at this section to reduce capacitances by increasing the distance from dump pad to vessel wall. However, this measure leads to an increase in shunt impedance for certain higher frequency modes for which the E-Field shape along the beam path remains relatively constant as the vessel size is increased. Thus the beam sees more of the field, causing the shunt impedance to increase for these modes. Additionally, the enlargement of the vessel shifts the existing resonant modes to lower frequencies, which is an unwanted effect.

It was therefore decided to enlarge the beam pipe aperture size at the vessel wall, tapering upward from the standard beam pipe. This enlargement away from the beam path reduces the longitudinal E-Field seen by the beam, and thus the resulting shunt impedance. In addition, this small geometrical adjustment does not shift the resonance frequency significantly downwards. A series of taper lengths were explored, along with aperture shapes. The aperture size is limited by vessel wall size and mechanical feasibility. Additionally, since the aperture is not centered on the vessel wall, one side is more limited in radius than the other, leading to a nonlinear elliptical taper shape. Comparison to a taper of circular cross-section showed that the rather complex non-linear taper offered only slightly improved performance than a circular one which does not motivate to select the mechanically more complex shape.

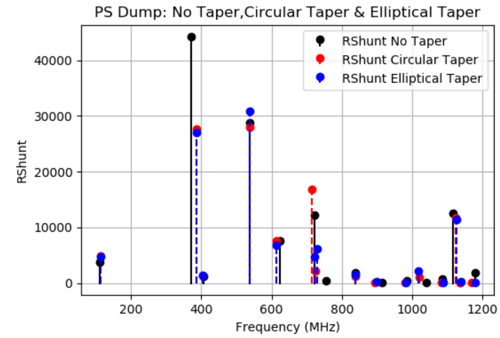

Figure 3: Eigenmode simulation results (R_{sh}) of the two taper designs (circular and elliptical) with the no taper design.

As is shown in Fig. 3, by adding the tapers, the mode at 372 MHz shifts upward in frequency to 385 MHz, together with a considerable reduction in shunt impedance from 44 kΩ to 27 kΩ.

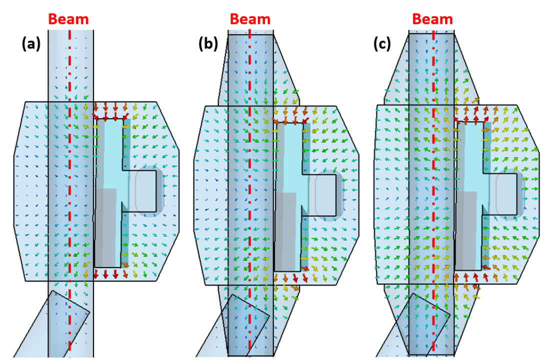

Figure 4: Electrical field patterns for the 385 MHz mode for the two taper designs (elliptical (b) and circular (c)), and without tapers (a) as a reference (mode at 372 MHz). The beam path is the red dotted line.

Figure 4 shows the mode at 385 MHz for both taper designs compared to no taper as a reference, with the beam path indicated in red. The E-Field plot is shown on a cut plane through the beam position (see Fig. 1). The dump pad cross-section is shown in the center. Note the E-Field lines going from the dump pad to the vessel walls, with a portion of them aligning parallel to the beam path (dotted line).

The other targeted mode at 722 MHz shifts in frequency with the addition of the tapers, with the elliptical shifting the mode to 713 MHz and the circular to 729 MHz. Interestingly for this mode, the circular taper has a higher R_{sh} (16 kΩ) than the elliptical taper case (6 kΩ), and even the no-taper design (12 kΩ). The cause for this is that circular taper modifies the field pattern such that there is slightly more longitudinal E-Field along the beam path compared to the no taper case. This is not the case for the elliptical taper due to its asymmetry.

The 540 MHz mode is almost unaffected by the addition of the tapers. Both taper designs have an R_{sh} of 28 kΩ. This

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is only a slight reduction of the R_{sh} (30 kΩ) of the design without a taper.

For other modes at 100 MHz and 610 MHz, the tapers have a negligible effect. The circular taper was chosen for its performance at 385 MHz and its slightly better performance than the elliptical taper at 540 MHz. Additionally, it is easier to fabricate.

HOM COUPLERS DESIGN

Further reduction of longitudinal beam impedance is best achieved by using HOM coupling loops placed in the magnetic field maxima of the undesired modes. For the modes at 385 MHz, 540 MHz and 713 MHz, the strongest magnetic fields are running parallel to the dump arm, with high field concentrations between the bottom of the tank and back of the dump pad. The coupling loops are placed at this location due to the strong fields and space available.

The loop length and its opening cross-sectional area are designed as large as possible to maximize coupling. The thickness of the loop was optimized to reduce the R_{sh} of the 385 MHz mode. The shape of the loop can be varied in thickness, this way offering a design knob for the 385 MHz and 540 MHz modes. Increasing thickness causes stronger electrical coupling to the 540 MHz mode, and thus reduces its shunt impedance, while at the same time, it decreases the magnetic coupling to the 385 MHz mode. The loop is terminated with a characteristic impedance of 50 Ohms; other impedances were explored but the performance increase was negligible. The loops are shown in Fig. 1, note that the beam path is not at the geometric center of the vessel, accounting for the offset from the cut-plane and the loops' positions.

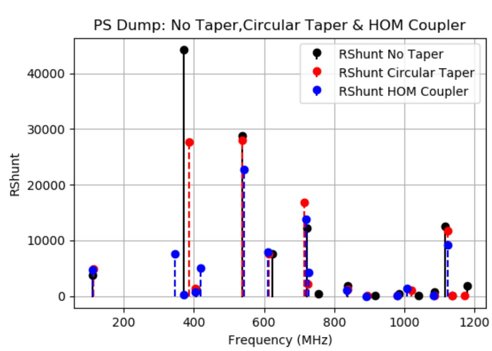

Figure 5: Shunt impedances calculated from the Eigenmode solutions of the PS dump model without tapers, with circular tapers and finally with the tapers and coupling loops.

Figure 5 shows the shunt impedance calculated from the Eigenmode solutions of the initial (no taper) design, circular taper, and the circular taper design with HOM couplers.

Note that with the HOM couplers there are additional modes around the original mode of 385 MHz, present at 346, 370, 404 and 419 MHz. The modes at 370 and 404 MHz are resonant modes that are concentrated at the loops, hence result in very small R_{sh}. The modes at 346 MHz (8 kΩ) and 419 MHz (5 kΩ) show field patterns nearly identical to that of the mode that was originally observed at 385 MHz (28 kΩ) for the circular taper design, with the loops disturbing the fields and reducing the R_{sh} greatly.

The mode at 540 MHz is shifted to 543 MHz and has had its R_{sh} reduced to 22 kΩ from 28 kΩ. Originally this mode was only negligibly disturbed by addition of just the taper. Finally the 713 MHz mode is shifted to 718 MHz and has an R_{sh} of 13.5 kΩ, which is reduced from the taper-only case (16 kΩ) but still not as low as the initial, no taper design (12 kΩ). These upward frequency shifts are to be expected since the loops are reducing the volume of the vessel slightly.

The 346 MHz mode's greater reduction in R_{sh} is a result of the stronger magnetic coupling than the 543 MHz and 718 MHz modes.

COMPARISON WITH CURRENT DUMP

Figure 6 shows the new dump with circular beam pipe tapers and HOM couplers compared to the dump that is currently installed in the PS. Overall the new dump has more modes than the presently installed one at the investigated frequency range below 1.2 GHz. This increase in modes is to be expected, since the geometry of the new dump is unavoidably larger than the old vessel, thus shifting resonances down in frequencies. It is of note that magnitude-wise, none of the new dump's modes have a higher shunt impedance than the current dump, especially at 400 MHz and 538 MHz.

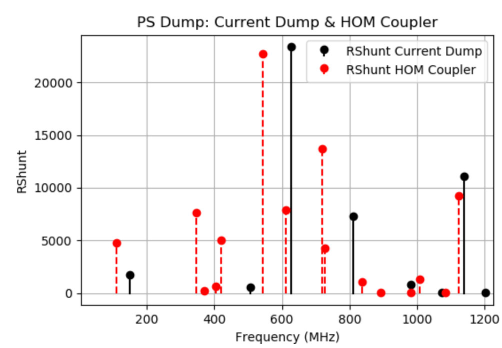

Figure 6: Shunt impedances calculated from the Eigenmode solutions of the PS dump model with the tapers and coupling loops compared to the presently installed PS dump.

CONCLUSION

The initial geometry of the new PS dump has undergone a design process to reduce its impedance. The first focus was on the design of tapers from the beam pipe to the dump's vacuum vessel, by which an impedance mitigation of the 385 MHz mode could be reached. Further measures concentrated on the reduction of the shunt impedances of the 385 and 540 MHz modes. A considerable improvement could be obtained by introducing specific HOM couplers on the lower part of the dump vessel. This addition of HOM couplers further reduced the impedance of the object.

Though this new design of the PS dump, even with the tapers and the HOM couplers, has more impedance contribu-

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tions than the currently installed dump, this is to be expected due to the larger volume of the structure. Once the object has been fabricated, EM-measurements will be done to confirm these results and the final impedance contribution will be added to the longitudinal impedance model of the PS.

REFERENCES

[1] CST AG, Darmstadt, Germany, http://www.cst.com

[2] G. Romagnoli *et al.*, "Design of the New PS Internal Dumps, in the Framework of the LHC Injector Upgrade (LIU) Project", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3521–3523, doi:10.18429/JACoW-IPAC2017-WEPVA109

[3] G. Romagnoli *et al.*, "Engineering Design and Prototyping of the New LIU PS Internal Dumps", presented at the 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, May 2018, paper WEPMG001.