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UPDATE OF THE TRANSVERSE PROTON SYNCHROTRON IMPEDANCE MODEL

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Abstract

The CERN Proton Synchrotron (PS) was recently upgraded to allow reaching the ambitious performance goal of the High-Luminosity LHC Project. This upgrade is part of the LHC Injectors Upgrade project. The final part of the upgrade was performed during Long Shutdown 2 (LS2) to allow injection at a higher energy from the PS Booster and a twofold increase in beam intensity and brightness. These changes must be considered in the PS impedance model. The effect on the impedance of the removal of obsolete injection equipment, changes of several accelerator components and new injection energy will be reviewed, as well as the wall impedance of the elliptic beam pipe, thanks to a newly developed code which allows to take into account both the ellipticity and the non-ultra-relativistic nature of the beam.

INTRODUCTION

The largest source of impedance in the PS is the resistive chamber wall from the beam pipe. The wall impedance $Z_\perp^{\mathrm{wall}}$ is classically divided into two parts: the resistive-wall impedance $Z_\perp^{\mathrm{RW}}$ and the indirect space charge $Z_\perp^{\mathrm{ISC}}$

$$Z_\perp^{\mathrm{wall}} = Z_\perp^{\mathrm{RW}} + Z_\perp^{\mathrm{ISC}}.$$

The resistive-wall impedance is defined as the contribution of the resistive part of the beam pipe to the total wall impedance [1]. It describes the effect of the bunch-produced electromagnetic fields interacting with the surrounding vacuum chamber of finite conductivity. The resistive-wall impedance is not limited to a single layer vacuum chamber case; a multilayered vacuum chamber resistive-wall impedance can be computed by matching the fields at each layer boundaries. The indirect space charge impedance is defined as the contribution that would be there if the wall were perfectly conducting [1] – it only depends on the vacuum chamber geometry.

Until recently the wall impedance of the elliptic pipe could only be computed approximately, through the Yokoya [2] factors. Many actors contributed over the years to the calculation of wall impedance: Zotter [3], and the codes ReWall [4], TLwall [5], and IW2D [6], to name a few. Thanks to recent developments, a new code allows to compute the wall impedance of a multilayered beam pipe of any elliptic geometry in the non-relativistic case. This newly obtained wall impedance is used in the PS impedance model. The range of validity of the Yokoya factors for a non-relativistic beam will also be discussed.

An accurate impedance model is crucial to assess the impact of impedance on beam dynamics for a beam of unprecedented brightness. An impedance model is considered complete when it can be compared with impedance induced beam observables measured in the machine. The outcome of this comparison allows confirming or not the validity of the model. If a large discrepancy is found between the model and beam measurements, new elements should be added. Iterating this process eventually leads to a model realistically reproducing the machine behaviour, and allowing predictions. In this paper the changes resulting from the LS2 will be assessed in terms of impedance and beam observables.

ELLIPTIC WALL IMPEDANCE OF A NON RELATIVISTIC BEAM

The PS beam pipe is composed of stainless steel and Inconel sections. The beam pipe geometry remains elliptical through most of the accelerator with a horizontal half axis of 73 mm and a vertical one of 35 mm [7]. The vertical plane is deemed the most critical in terms of impedance given its smaller aperture.

For an ultra-relativistic case, it is possible to compute an elliptic wall impedance using Yokoya form factors [2]. Yokoya form factors consist of geometric factors to apply to the round case impedance in order to properly account for the desired geometry. However this method is in principle valid only for the ultra-relativistic case and in a limited frequency range.

In [8] it was shown that the form factors depend not only on the geometry but also on the wave number in free space k_0, the relativistic beta β and the relativistic mass factor γ. In other words the generalized form factors are in fact functions of the geometry and the frequency. When reaching the ultra-relativistic regime, $\beta \to 1$ and $\gamma \to \infty$ thus the parameter $k_0/\beta\gamma \to 0$, the form factors become constant with frequency and only depend on the geometry. Nevertheless the usual Yokoya form factors should remain valid for small values of $k_0/\beta\gamma$.

By considering the pre-LS2 injection case, γ is set to 2.49 . At low γ, non ultra-relativistic effects are present, in particular from indirect space charge. Plotting the usual Yokoya form factors next to the generalized form factors as shown in Fig. 1 leads to three observations.

The first one is that the Yokoya form factors agree almost perfectly with the generalized ones for the real part of the

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impedance up to 1 GHz. The second observation is that a small difference is observed with the form factors for the imaginary part of the impedance below 1 GHz. The difference is due to the presence of the indirect space charge. Finally above 1 GHz a large difference starts to appear for both the real and imaginary parts, between the Yokoya and the generalized form factors obtained from the code of Migliorati et al. [8]. It can be correlated with the fact that the parameter $k_0/\beta\gamma$ ($\approx$ 10) starts being larger than one.

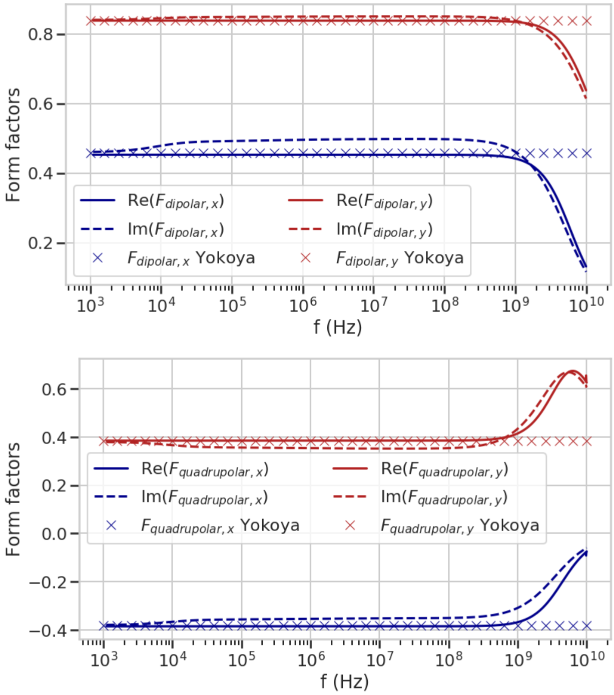

Figure 1: Dipolar and quadrupolar form factors as a function of frequency for the PS elliptical beam pipe at $\gamma = 2.49$.

Migliorati et al. [8] found a similar behaviour for the case of the CERN Proton Synchrotron Booster (PSB) with a different energy and geometry than the case of the PS. They could see elliptic impedances (with Yokoya and generalized form factors) starting to differ around $k_0/\beta\gamma \approx 10$. Hence the Yokoya form factors can be used for non ultra-relativistic cases if the parameter $k_0/\beta\gamma$ is small.

PS IMPEDANCE MODEL

Pre Long Shutdown 2 Impedance Model

The current PS transverse impedance model is the result of the work of several colleagues over the years: in particular recently S. Persichelli [9], D. Ventura, N. Biancacci, who gradually introduced elements in the model until beam observables could be reproduced. The PS impedance model before LS2 was composed of the low frequency contribution from the beam pipe, and a number of high frequency contributions (and HOMs) from kickers, cavities, septa, vacuum ports, bellows, vacuum valves, metallic flanges, step transitions, BPM and Finemet cavities. Their individual contributions to the global vertical impedance have been highlighted in Fig. 2.

The high frequency impedance contribution (above hundreds of MHz) originates mainly from the kickers, bellows and vacuum ports. Regarding the low frequency impedance contribution, the main contributor is the wall impedance. While the low frequency impedance contribution has a much larger amplitude than the high frequency one, both are equally important to properly simulate the machine behaviour.

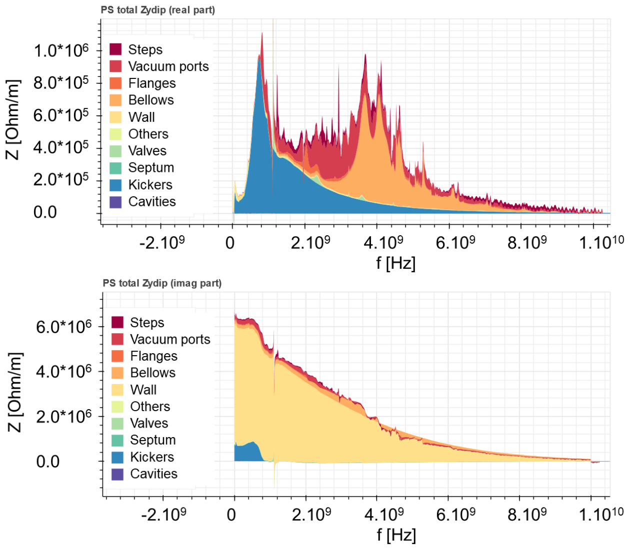

Figure 2: Frequency spectra of the real and imaginary parts of the impedance for different machine elements.

Most of the impedance contributions were calculated using the simulation code CST Particle Studio. A complete layout of the machine and the specific elements taken into account in the impedance model can be found in [10].

Changes Introduced by Long Shutdown 2

In this section we limit ourselves to changes impacting the transverse impedance budget of the machine. One example is the removal of the obsolete Continuous Transfer (CT) equipment [11], i.e. kickers (BFA09, BFA21) and an electrostatic septum (SEH31). Removing this equipment leads to a small, yet beneficial, impedance reduction for each impedance component (see Fig. 3).

At injection, the most important change in terms of impedance during the Long Shutdown 2, is the increase in injection kinetic energy from 1.4 to 2.0 GeV – this reduces the effect of indirect space charge, hence the imaginary part of the wall impedance (see Fig. 4).

The indirect space charge effect is predominant in the hundreds of MHz to the GHz range. When the energy is increased from 1.4 GeV to 2.0 GeV, the imaginary part of the wall impedance is decreased by up to ≈ 25%. Since the wall impedance accounts for a large part of the total machine impedance budget, a decrease in the imaginary part of the impedance is clearly beneficial.

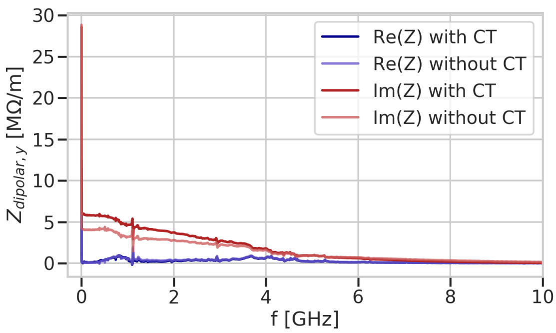

Figure 3: Impedence spectrum with and without the Continuous Transfer equipment without considering the wall impedance.

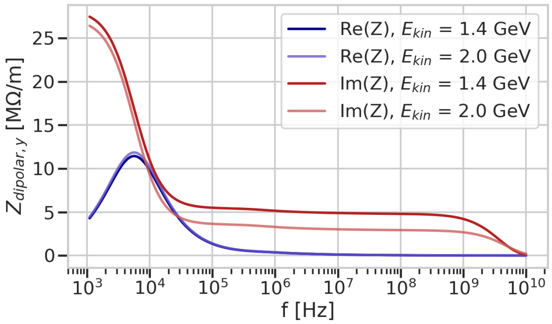

Figure 4: Effect of the injection energy on the vertical dipolar wall impedance.

Kickers represent another large impedance contribution and the most critical one at high frequencies. The accuracy of impedance simulation using CST has been improved [12], by using a shorter Gaussian bunch to excite higher frequencies and by using more mesh cells. As a result, one can observe a better resolution for the peak around 1 GHz, as well as a number of modes at higher frequencies (see Fig. 5).

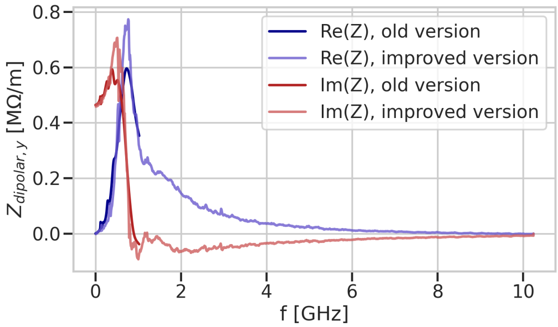

Figure 5: Comparison of the impedance simulation of the KFA kickers, with improved simulation accuracy.

Taking all these changes into account, one can compare the imaginary part of the vertical dipolar impedance (Fig. 6), responsible for the tune shifts, pre and post LS2 (Fig. 7). The hardware modifications accounts for a ≈ 15% change in tune shift. Whereas the higher injection energy results in a ≈ 92% smaller vertical tune shift.

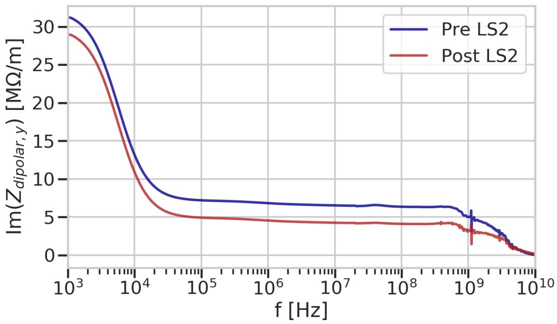

Figure 6: Imaginary part of the vertical dipolar impedance pre and post LS2.

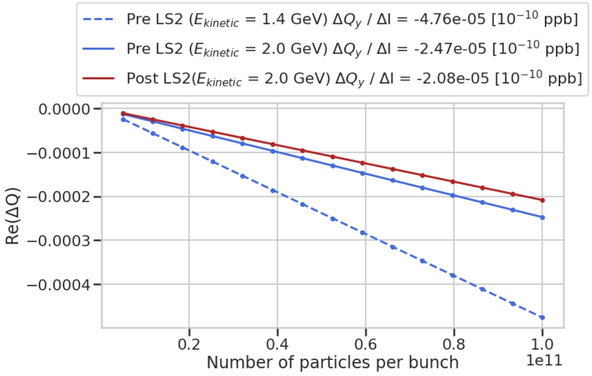

Figure 7: Vertical tune shifts (computed with DELPHI Vlasov solver) with and without matching injection energy.

CONCLUSION

A new method to compute the wall impedance of an elliptic beam pipe at any energy has been applied to the case of the PS. Using this method we show that the Yokoya form factors remain valid for a non ultra-relativistic beam up to a certain threshold. A brief overview of the PS transverse impedance model pre LS2 and the main contributors to the impedance budget was shown. Changes induced by the LS2 were listed and their effects assessed in terms of transverse impedance.

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