UPDATE OF THE SPS IMPEDANCE MODEL

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Abstract

The beam coupling impedance of the CERN SPS is expected to be one of the limitations to an intensity upgrade of the LHC complex. In order to be able to reduce the SPS impedance, its main contributors need to be identified. An impedance model for the SPS has been gathered from theoretical calculations, electromagnetic simulations and bench measurements of single SPS elements. The current model accounts for the longitudinal and transverse impedance of the kickers, the horizontal and vertical electrostatic beam position monitors, the RF cavities and the 6.7 km beam pipe. In order to assess the validity of this model, macroparticle simulations of a bunch interacting with this updated SPS impedance model are compared to measurements performed with the SPS beam.

INTRODUCTION

Machine studies performed in the CERN SPS since 2002 have shown that the SPS beam coupling impedance could be a limitation for reaching the LHC upgrade expected beam intensity [1].

In the SPS, these observations have triggered a detailed study of the impedance and the creation of a database of the longitudinal and transverse impedances of the elements of the SPS machine. This database takes advantage of the philosophy and tools of the existing LHC impedance database ZBASE [2].

In this paper, the general framework described in [3] was applied to compute a more accurate transverse impedance model of the SPS from theoretical models for the 20 kickers installed in 2006 and the 6.9 km long beam pipe, as well as time domain electromagnetic simulations of the 106 (resp. 96) horizontal (resp. vertical) beam position monitors (BPHs resp. BPVs), and 4 Travelling Wave (TW) 200 MHz RF cavities. Comparing HEADTAIL macroparticle simulations [4] to beam-based measurements in the SPS, this transverse impedance model turned out to account for 60% of the vertical impedance deduced from coherent tune shift measurements in the machine and showed in addition that the large negative quadrupolar horizontal impedance of the kickers can be held responsible for the measured positive coherent horizontal tune shift with increasing beam intensity.

IMPEDANCE OF SINGLE ELEMENTS

The calculations and/or simulations of the elements accounted for in the SPS model have been reported elsewhere (CST Particle Studio (PS [5]) simulations of the BPH and BPV [6], theoretical calculation of the beam pipe model [7] and of the kickers model following the formalism of Tsutsui [8]), except for the Travelling Wave 200 MHz RF cavities.

EM Simulations of the 200 MHz RF Cavities

A 3D model of an 11-cell-section of the SPS TW 200 MHz RF cavities was generated with CST Particle Studio from an initial model created for earlier versions of MAFIA by B. Spataro et al (see Fig. 1).

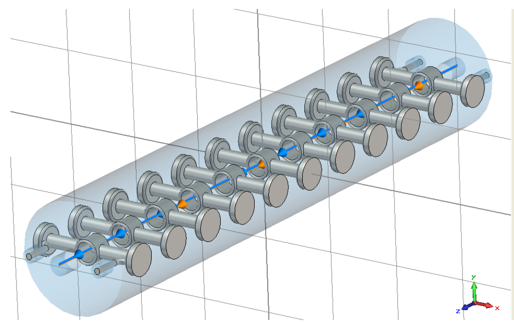

Figure 1: 3D model of a section of 11 cells of the SPS Travelling Wave 200 MHz RF cavities generated with CST Particle Studio [5]. Two models for ideal couplers can be seen at each end of the cavity next to the beam pipe.

In the SPS, two cavities (ACTA and ACTB) are made of 4 aggregated sections of 11 cells, while two other cavities (ACTC and ACTD) are made of 5 aggregated sections of 11 cells. CST simulations (v.2010 beta) to obtain the horizontal and vertical, dipolar (dip) and quadrupolar (quad) wake potentials were performed with an rms bunch length of 2 cm and more than 6 million mesh cells. The wake potentials for the sum of all 4 cavities - a total of 18 sections of 11 cells without couplers, making the assumption that the wake potentials

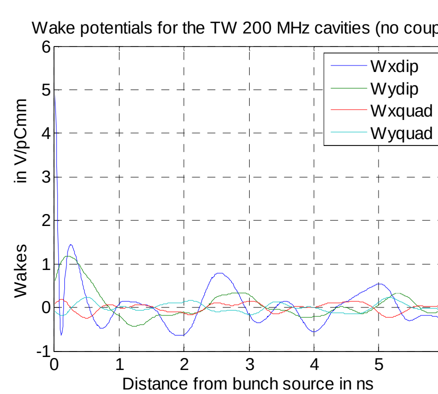

Figure 2: Wake potentials simulated with CST Particle Studio (rms bunch length 2 cm).

of separate sections can be summed - are presented in Fig. 2.

As explained in [3], corrections were applied to account for the corresponding beta functions loaded from the SPS optics file for each cavity. It is also important to note that only the horizontal dipolar wake (Wxdip) could not be calculated using the “indirect testbeams’ integration method, resulting in a large oscillation very close to the bunch. Besides, it can be checked that the horizontal and vertical quadrupolar wakes are equal in amplitude but opposite in sign.

The dipolar and quadrupolar impedances computed from these wake potentials (as in [3]) are shown in Fig. 3.

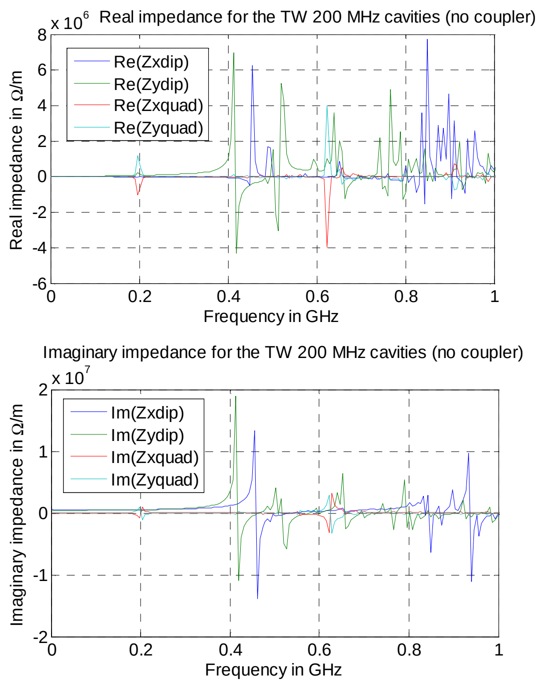

Figure 3: Real (top) and imaginary (bottom) impedance obtained from the wake potentials simulated with CST Particle Studio (rms bunch length 2 cm).

The longitudinal and transverse resonant impedances of the SPS had been listed in [9]. In that paper, the first longitudinal resonances were mentioned to be at 200 MHz and 629 MHz while the transverse resonances were mentioned to be at 460 MHz and 938.5 MHz.

It should be noted that the two main resonances in the longitudinal impedance simulated by CST Particle Studio are at 200 MHz and 621 MHz (not shown here). Besides, in Fig. 3, we can see that the horizontal dipolar resonances (in blue) are located at frequencies very close to these predicted above (455 MHz and 934 MHz) together with other resonances (at 850 MHz for instance). The impedance spectrum for the vertical dipolar impedance appears to be shifted to lower frequencies (413 MHz and 770 MHz) with a strong additional resonance at 520 MHz. As it was already found out for the case of the kickers and the BPMs, the quadrupolar impedance shares similar features with the longitudinal impedance as the main quadrupolar resonances in light blue and red are also found at 200 MHz and 622 MHz. Since the source beam is the same for obtaining both quadrupolar and longitudinal, these similarities are likely not a coincidence and will be studied in detail to try and find a more general link between the longitudinal and transverse quadrupolar impedances.

Finally, the low frequency imaginary impedance in Fig. 3 is 0.4 MΩ/m for both dipolar impedances, -0.01 MΩ/m for the horizontal quadrupolar impedance and 0.01 MΩ/m for the vertical quadrupolar impedance. The tune shift caused by the RF cavities’ transverse wake is therefore expected to be small.

UPDATED SPS WAKE MODEL

The RF cavities wake was added to the SPS model described in [3] in order to get an updated wake model for the SPS accounting for the beam pipe, BPHs, BPVs, kickers and 200 MHz TW RF cavities. The small difference between the former (red) and new (blue) models can be seen in Fig. 4.

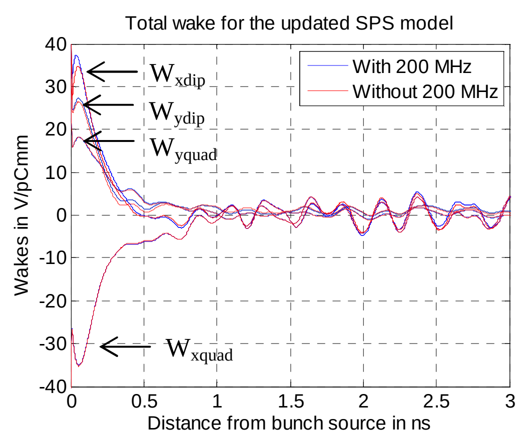

Figure 4: Wake potentials simulated with CST Particle Studio (rms bunch length 2 cm).

MACROPARTICLE SIMULATIONS WITH THIS UPDATED MODEL

The HEADTAIL code was used to simulate a bunch of macroparticles interacting with the SPS wake model obtained in the previous paragraph. The relevant simulation initial parameters for the low emittance (0.15 eVs) bunch at injection in the SPS are the same as in reference [3]. In particular, the initial rms bunch length is σ = 0.15 m; chromaticity, space charge, linear coupling or amplitude detuning are not considered; all impedances are lumped in one location. However, we now consider a non linear bucket.

Scanning the simulated bunch population from N_b = 1. 10^9 to 1.5 10^{11} protons per bunch (p/b), a first small instability threshold is observed in the vertical plane at N_b = 3.5 10^{10} p/b and is linked to the coupling of radial modes of azimuthal modes 0 and -1 (see Fig. 5).

Increasing N_b over 4.5 10^{10} p/b, the vertical motion becomes stable again and is indeed strongly damped and it is interesting to notice that the main mode is not mode 0 but mode -1. Increasing N_b over 8.5 10^{10} p/b leads to an instability that seems to be due to a coupling between radial modes of azimuthal modes -1 and -2.

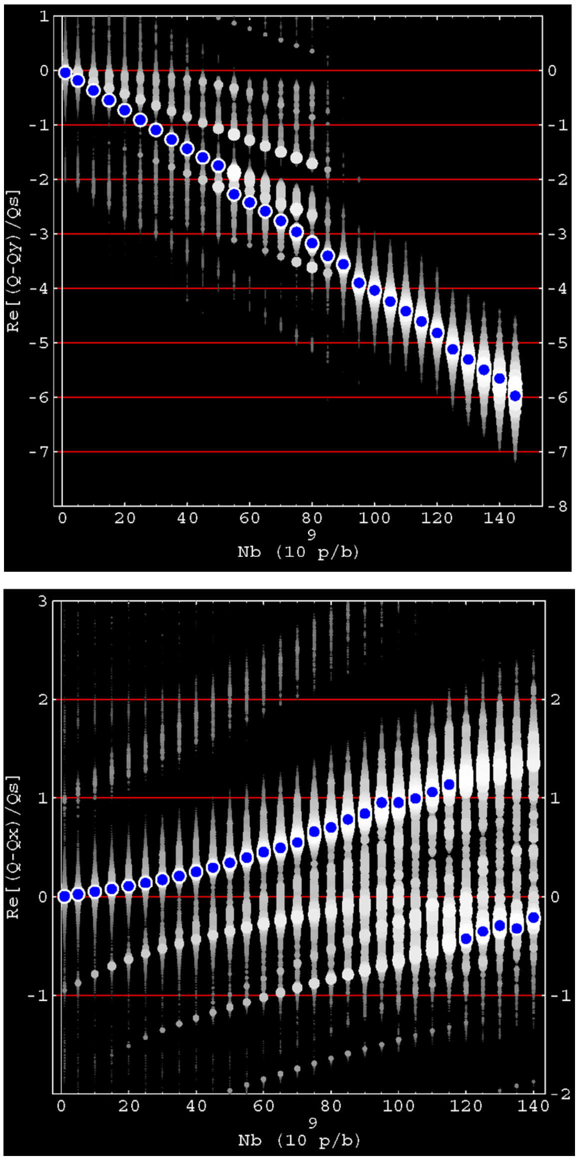

Figure 5: Vertical (top) and horizontal (bottom) mode spectra of the HEADTAIL simulated motion of an SPS bunch with increasing intensity interacting with the updated SPS impedance model. The size and brightness of the dots increases with the spectral amplitude. The mode with the largest spectral amplitude is plotted in blue. The bucket is non linear.

The effective impedances obtained from the low intensity slope of tune with intensity with Sacherer's equation for the frequency shift of mode 0 with a Gaussian bunch [10] are 13.8 MΩ/m for the vertical plane and -2.1 MΩ/m in the horizontal plane. It is interesting to note that the updated impedance model is not constant at low frequency, making it hazardous to scale the results at one bunch length to another bunch length. Indeed, simulating a longer bunch closer to the nominal parameters (rms bunch length σ = 0.3 m) interacting with the same updated SPS model with HEADTAIL yields a vertical effective impedance of 15.1 MΩ/m [11].

CONCLUSION AND FUTURE WORK

Dipolar and quadrupolar wake functions calculated from theoretical models of the beam pipe and kickers were summed with dipolar and quadrupolar wake potentials obtained from EM simulations of BPH, BPV and RF TW 200 MHz cavities to obtain a updated wake model of the SPS. This wake model was used as input of HEADTAIL macroparticle simulations and turned out to account for about 60 % of the measured vertical tune shift (13.8 instead of 23.6 MΩ/m) and 80 % of the measured horizontal tune shift (-2.1 MΩ/m instead of -2.6 MΩ/m). The simulated instability threshold is now very close to the measured threshold (8.5 10^{10} p/b instead of 7.5 10^{10} p/b).

However damping mechanisms present in the machine were not included in the simulations, so that this threshold is likely to be significantly underestimated. As a consequence, even though our understanding of the SPS impedance increased, the search for other significant impedance sources continues. At the moment, suspected elements are the septa, the 800 MHz cavities and non shielded pumping ports studied in [12].

ACKNOWLEDGMENTS

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