AN UPDATE OF ZBASE, THE CERN IMPEDANCE DATABASE

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Abstract

A detailed knowledge of the beam coupling impedance of the CERN synchrotrons is required in order to identify the impact on instability thresholds of potential changes of beam parameters, as well as additions, removals or modifications of hardware. To this end, an update of the impedance database was performed, so that impedance results from theoretical calculations using new multilayer models, impedance results from electromagnetic field simulations and impedance results from bench measurements can be compiled. In particular, the impedance database is now set to separately produce the dipolar and quadrupolar transverse impedance and wakes that the *Headtail* simulation code needs to accurately simulate the effect of the impedance on the beam dynamics.

INTRODUCTION

Machine studies performed in the CERN SPS since 2002 have shown that 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, recent transverse impedance results from theoretical calculations and electromagnetic (EM) simulations of SPS accelerator equipments are obtained, compiled, and converted into wake fields, and used as inputs of the *Headtail* macroparticle simulation code [3] in order to predict the SPS beam behaviour.

GATHERING IMPEDANCE RESULTS

The total impedance of a ring is classically assumed to be the sum of the separate impedance contributions of all machine equipments. The impedance of an element can be measured on an RF bench using the single and double wire methods [4]. It can also be simulated with electromagnetic codes such as CST *Particle Studio* and *MAFIA* or *GdfidL* [5]. Finally, the impedance of simple structures can be obtained as solutions of analytic formulae [6].

In our case, the longitudinal and transverse impedances of several SPS kickers have been measured [1, 7, 8], the impedance of the SPS beam pipe (see Fig. 1) and other kickers has been estimated by theoretical calculations [1], and the impedance of the SPS beam position monitors (BPH and BPV) have been simulated with CST *Particle Studio* [9].

It is important to point out that the objective of the database is to obtain a wake function that could be an input of *Headtail* simulations. The *Headtail* code currently models the interaction of the bunch with the transverse impedance by dipolar kicks that depend linearly on the position of the source charge, and quadrupolar kicks that depend linearly on the position of the test charge. As a consequence, the impedance or wake contributions produced by theory, EM simulations or bench measurements have to be processed into dipolar and quadrupolar wake functions.

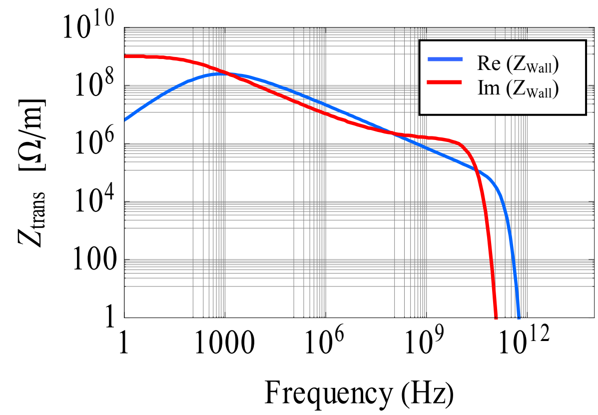

Figure 1: Transverse Wall impedance for a model SPS Beam Pipe (round Stainless Steel pipe, with 2 cm radius and 6911 m length, relativistic gamma $\gamma = 27.7$). The wall impedance formula contains both the resistive wall and the perfect conductor wall - also called indirect space charge - contributions of the impedance [10].

COMPUTING DIPOLAR AND QUADRUPOLAR WAKE FUNCTIONS

Theoretical Calculations

Theoretical calculations give the transverse impedance as a function of frequency for an axisymmetric structure [6] (see Fig. 1). The wake function can be obtained by a Discrete Fourier Transform (DFT) of this impedance. In Wall impedance case, the interesting impedance range spreads over many frequency decades and built-in DFT with constant frequency sampling may reach the available memory limits. Wake functions obtained with several frequency ranges and frequency sampling are shown in Fig. 2. In this case, if the frequency sampling is too low (1 MHz), the long range wake is not correctly obtained (see Fig. 2 (a)). Besides, if the impedance is truncated at too low frequencies (0.1 THz or lower), unphysical wake oscillations appear (see Fig. 2 (b)). A fair trade-off has to be found.

Table 1: Form Factor Coefficients for Round/Flat Chambers.

geometry	X dip.	X quad.	Y dip.	Y quad.
Round	1	0	1	0
Flat	$\pi^2/24$	$-\pi^2/24$	$\pi^2/12$	$\pi^2/24$

Besides, for simple geometries, the dipolar and quadrupolar contributions can be obtained with form factor coefficients [1]. The SPS beam pipe aperture in the horizontal (X) plane is much higher than the aperture in the vertical (Y) plane, so that a flat model can be used. The form factor coefficients are given in Table 1.

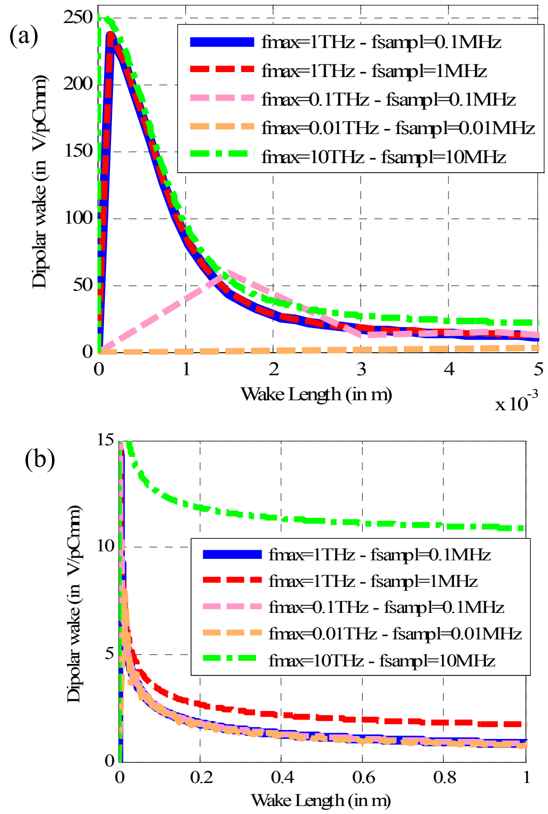

Figure 2: Transverse wake function obtained by DFT of the impedance shown in Fig. 1 up to 5 mm (a), and up to 1 m (b) for different frequency samplings (0.01 MHz to 10 MHz) and frequency span (0.01 THz to 10 THz). The wake obtained from the largest number of impedance points (blue thick line, 0 to 1 THz with a sampling of 0.1 MHz, i.e. 10^7 points) seems to be a fair compromise at both low (a) and high (b) distance to the source charge.

After this postprocessing, the wakes calculated for the SPS beam pipe is ready to be imported into *Headtail*.

Further dipolar and quadrupolar wake functions for the SPS kickers were obtained with analytical calculations and imported into *Headtail* [1].

Electromagnetic Simulations

Time domain simulations calculate the longitudinal and transverse wake potentials created by a source bunch traversing the structure. Four combinations of transverse displacements of the source bunch and the wake calculation paths enable to obtain the 4 linear wake contributions needed for *Headtail*, as shown in Table 2. It is important to note that (1) the wakes obtained have to be normalized by the displacement *a*, and (2) this displacement *a* should remain small to remain in the linear region (less than 10 % of the aperture in our case). This last remark also implies that *Headtail* assumption of linear kicks with transverse displacement should only be valid for small displacements.

Table 2: Source bunch and wake calculation transverse location (x,y) combinations to obtain the dipolar and quadrupolar wake potentials from EM simulations.

Transverse location	X dip.	X quad.	Y dip.	Y quad.
Source	(a,0)	(0,0)	(0,a)	(0,0)
Test path	(0,0)	(a,0)	(0,0)	(0,a)

The dipolar and quadrupolar wake potentials for the SPS BPH and BPV have been simulated with CST *Particle Studio* [9] using a finite length bunch. If the simulated bunch is small enough, the wake potential can be used as a good approximation of the wake function. However, very small simulated bunches lead to huge number of simulated mesh cells, so that the simulated bunch has to remain large (in our case 5 mm to 1cm rms). These wake potentials have therefore been deconvolved from the source bunch charge distribution. This implies a DFT to go to the frequency domain followed by a division by the source frequency distribution, and an inverse DFT to come back to time domain. These steps have to be performed carefully in order to avoid amplifying the simulation numerical noise or unphysical oscillations due to signal truncation. The BPH dipolar and quadrupolar wake functions are shown in Fig. 3. One should note that the horizontal and vertical quadrupolar contributions of the wake do not follow $W_{x,quad} = - W_{y,quad}$. These wakes, as well as wake functions obtained for the SPS BPV are now ready to be imported into *Headtail*.

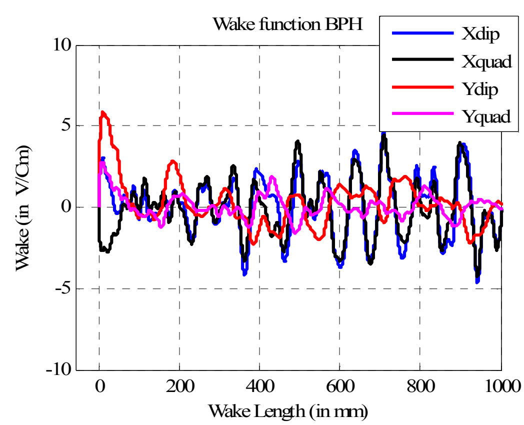

Figure 3: Transverse wake functions for an SPS BPH obtained from CST Particle Studio simulated wake potentials. Linear dipolar and quadrupolar contributions are obtained for each plane by displacing both source bunch and wake calculation transverse locations as explained in Table 2.

RF Measurements

The RF measurements performed until now were mainly dedicated to obtain the transverse total impedance (sum of dipolar and quadrupolar contributions) with a single wire displaced, or the dipolar contributions with the two wire technique, but rarely both. For simple geometries with symmetries, using one or the other technique to obtain the impedance is enough to compute all dipolar and quadrupolar contributions for *Headtail*. However, most devices have rather complicated geometries for which the form factor can not be applied.

From now on, wire measurements will be performed to specifically obtain the dipolar and quadrupolar linear contributions of the impedance.

WAKES AS INPUT FOR SIMULATIONS

All dipolar and quadrupolar wakes obtained for each available SPS element (SPS kickers, beam pipe and all BPMs) can be weighed by the respective β function at their location and summed (see Fig. 4). From this graph, the SPS kickers have the largest contribution to the vertical wake functions, and all the BPMs have a small contribution, at least on the single SPS bunch range.

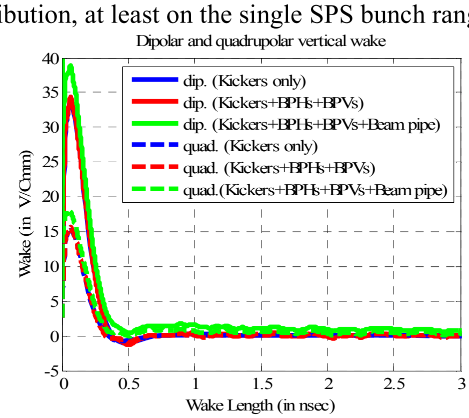

Figure 4: Vertical dipolar and quadrupolar wakes for the summed β-weighed contributions of the SPS kickers, the wall impedance of the beam pipe and all BPHs and BPVs.

Headtail simulations were performed using these wake functions as inputs. The simulation parameters were the same as in ref. [11]. Direct space charge was not included in the simulations. The simulated vertical tune shifts and growth rates are shown in Fig. 5. It is interesting to notice the significant effect of the beam pipe on both the tune shift (Effective impedance becomes 12.8 MΩ/m instead of 9.5 MΩ/m) and the main instability threshold, at which coupling between modes -2 and -3 occurs (threshold decreases from 9.4 10^{10} protons to 7.4 10^{10} protons).

CONCLUSION AND FUTURE WORK

Wake functions calculated from SPS beam pipe and kickers theoretical models were summed with wake functions obtained from EM simulations of BPH and BPV to obtain dipolar and quadrupolar wake functions, which were used as inputs of *Headtail* macroparticle simulations. These simulations confirm that the kickers are major contributors to the impedance compared to the BPMs or the beam pipe.

Now that the procedures have been set for EM simulations, impedance calculations and RF measurements, it will be interesting to obtain the dipolar and quadrupolar wake functions of other potential SPS impedance contributors. Also, some assumptions to the models used will be refined (laminated steel instead of ferrite kickers) and simulations should be compared with beam measurements.

ACKNOWLEDGMENTS

We would like to thank G. Arduini, O. Brüning, F. Caspers, J. Jowett, N. Mounet, and B. Zotter for their help and advice.

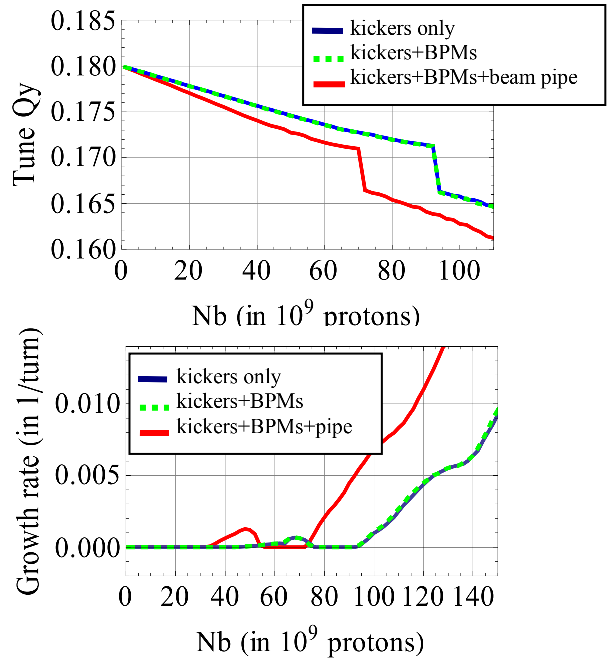

Figure 5: Vertical tune shifts and growth rates obtained from *Headtail* simulations with Fig. 4 wake functions as inputs.

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