COUPLING IMPEDANCE OF THE CERN SPS BEAM POSITION MONITORS

B. Salvant (EPFL and CERN, Switzerland), G. Arduini, C. Boccard, F. Caspers, A. Grudiev, R. Jones, E. Métral, G. Rumolo, C. Zannini (CERN, Switzerland), B. Spataro, D. Alesini, M. Migliorati, (INFN Frascati, Italy), F. Roncarolo (UMAN, Manchester, UK), R. Calaga (BNL, NY, USA).

Abstract

A detailed knowledge of the beam coupling impedance of the CERN Super Proton Synchrotron (SPS) is required in order to operate this machine with a higher intensity for the foreseen Large Hadron Collider (LHC) luminosity upgrade. A large number of Beam Position Monitors (BPMs) is currently installed in the SPS, and this is why their contribution to the SPS impedance has to be assessed. This paper focuses on electromagnetic (EM) simulations and bench measurements of the longitudinal and transverse impedance generated by the horizontal and vertical BPMs installed in the SPS machine.

INTRODUCTION

Machine studies performed at the CERN SPS since 2002 have shown that single-bunch proton beams with low longitudinal emittance are affected by heavy losses after less than one synchrotron period following injection as a result of a fast vertical instability [1,2].

These observations have triggered a detailed study of the impedance of the main elements of the SPS machine in order to complete the work already started in the longitudinal plane at the end of the nineties [3] and to create a database of the longitudinal and transverse impedances of the elements of the SPS machine.

The results of electromagnetic field simulations of the Horizontal (BPH) and Vertical (BPV) beam position monitors are discussed in the next paragraphs. These elements have been chosen because of their large number (106 BPH and 96 BPV in 2006's run). The shape and materials of these SPS BPMs are not trivial and to our knowledge there is no theory to predict their beam coupling impedance. As a consequence, bench RF measurements were also performed to benchmark the simulation results with available measured observables.

EM SIMULATIONS SETUP

The geometric structures of the BPH and BPV were first generated with the first version of MAFIA [4], but all geometries and simulation results presented here were obtained with CST Studio Suite [5]. Pictures of an actual BPH are shown in Fig. 1, and 3D representations of an SPS BPH used for simulations in Fig. 2.

Many simplifications were applied to obtain the modelled geometry used for the simulations: (1) the outer cylindrical shell and the cavity between this shell and the rectangular inner body observed in Fig. 1 (a) were not modelled, thereby assuming the fields created by the beam can not reach beyond the inner body. (2) Several features of the inner casing were removed (electrodes' screws, brass calibration plates, ceramic plots) or simplified (perfectly matched electrode coaxial port, casing to beam pipe transition, shape of the beam pipe cross-section, mechanical tolerances). (3) The SPS BPM inner body is in Anticorodal B [6], and both the electrodes and the beam pipe are in Stainless Steel 304L. However, all metallic parts of the simulated BPMs were assumed to be made of perfect conductors (PEC).

These simplifications are assumed to have a smaller impact on the results than the coupling between the cavities behind the electrodes and the main cavity through which the beam traverses.

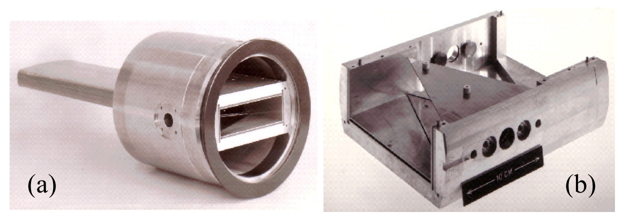

Figure 1: Pictures of an SPS BPH: full BPH assembly (a), and partly dismantled BPH inner body (b).

CST Particle Studio's Wakefield Solver was used to obtain the wake potential generated by the passage of a gaussian bunch through the BPM. The Beam Coupling Impedance of the BPM is also automatically post-processed from this wake potential. The Eigenmode solver of CST Microwave Studio was used to obtain the parameters of the modes trapped in the structure (resonance frequency f_{res}, shunt impedance R_s and quality factor Q).

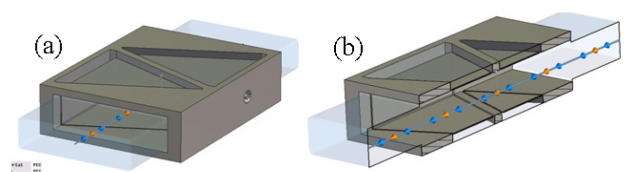

Figure 2: Model of the SPS BPH: (a) Beam path and wake integration path are shown with blue and orange arrows. Using a cut plane (b) reveals the inner structure of the BPH body: a pair of bi-triangular shaped electrodes isolated from the rest of the casing with vacuum cavities. Beam entry and exit planes are perfect matching layers, and all other boundaries are PEC.

TIME DOMAIN SIMULATIONS

For the following CST Particle Studio simulations, the 15 meter wake potential left by a 1 cm rms bunch in a BPH model made of 1 million mesh cells was calculated using the indirect testbeam wakefield solver. The vertical impedance of the SPS is more critical, and this why only results for the vertical impedance are shown in Fig. 3. The simulated wake potential oscillations do not decay within a reasonable simulated time. This is why additional frequency domain simulations are needed to obtain more accurate parameters for each of the resonance modes. Besides, the sign convention used in this paper is that inductive contributions are positive.

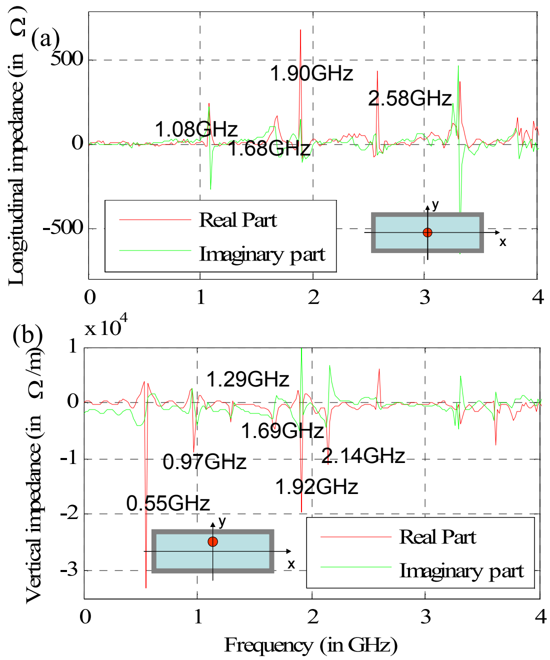

Figure 3: SPS BPH: longitudinal impedance (a) and total (dipolar + quadrupolar contributions) vertical impedance (b) spectra. The main resonance frequencies are displayed by the peaks. The total vertical impedance is normalized to the 5 mm vertical displacement.

The SPS BPH longitudinal wake potential was obtained by simulating a bunch passing at the transverse center of the beam pipe, and calculating the longitudinal wake along z also at (x,y)=(0, 0), as depicted in the sketch within Fig. 3 (a). The SPS BPH total transverse wake potential was obtained by displacing transversally both beam and transverse wake calculation location from the center of the beam pipe (see sketch within Fig. 3 (b)).

From these simulations, the low frequency imaginary impedance for a BPH is obtained: $Z_{//}/n \sim 1$ mΩ, Z_x=-0.1 kΩ/m and Z_y=2 kΩ/m. Separate simulations for a BPV give $Z_{//}/n$~0.5mΩ, Z_y= 0.1 kΩ/m and Z_x= 0.2 kΩ/m.

FREQUENCY DOMAIN SIMULATIONS

The AKS eigenmode solver of CST Microwave Studio was used to obtain the parameters of the most significant longitudinal and vertical resonance modes up to 2 GHz of the SPS BPH and BPV (see Tab. 1). The geometrical model and mesh used for the frequency domain and time domain simulations is the same, only the boundary conditions have to be set everywhere to *Electric* (except the ports). The parameters of the modes were obtained with the CST Microwave Studio post processing tool ($R_s=|V|^2/P_{losses}$). The longitudinal impedance modes are characterized by significant longitudinal shunt impedance when the integration of the longitudinal electric field is performed on center (2nd column of Tab. 1).

Table 1: Longitudinal and vertical SPS BPH modes.

f_{res} (GHz)	Rs (y=0mm) [Ω]	Rs (y=5mm) [Ω]	Q
0.55	$\sim 10^{-6}$	3.6	2100
1.08	9.43 10^{4}	9.26 10^{4}	3270
1.20	$\sim 10^{-6}$	6480	8000
1.30	$\sim 10^{-5}$	130	2680
1.64	$\sim 10^{-3}$	9.58 10^{3}	4060
1.69	167	169	2100
1.80	$\sim 10^{-6}$	1280	13700
1.88	5.79 10^{5}	5.67 10^{5}	3630
1.92	$\sim 10^{-2}$	230	6580

From the Panofsky-Wenzel theorem [7], vertical impedance modes are characterized by significant transverse gradient of the longitudinal impedance. Therefore, significant difference between the longitudinal shunt impedance calculated at a vertical displacement (3rd column) and on center (2nd column) indicates a vertical mode.

With one exception, the frequencies of both longitudinal and vertical resonance modes obtained in frequency domain (Tab. 1) are in agreement with the peaks observed in the time domain simulations (Fig. 3). High form factors Rs/Q values (150 Ω for f_{res}=1.88 in particular) are reported in frequency domain. However such thin slotlines like the ones coupling the cavities between the electrodes and the beam pipe have been reported to generate high Rs/Q factors [8].

In order to further crosscheck these simulations before using them in the SPS impedance database, bench RF measurements were also performed.

BENCH RF MEASUREMENTS

A BPV and a BPH have been made available for bench measurements. A BPH measurement with a bar as exciting source had already been performed [9]. However, in our case, several arguments advocate against setting a wire inside the BPMs to perform the classical wire measurement [10] (radioactive BPMs, small impedance signal expected, tampering with the BPMs would mean reconditioning them). The adopted strategy was therefore to measure S-parameters from the available N-ports at the BPM electrodes, and to benchmark these measurements with S-parameters CST Microwave Studio simulations. It is important to note that these S-parameters simulations and measurements are not direct impedance measurements, but they could help validate or invalidate the assumptions and modelling choices. A Vector Network Analyzer is used to measure S_{11}, S_{22} and S_{21} at the electrodes' ports. The transmission S_{21} simulation and measurements for the SPS BPH and BPV are gathered in Fig. 4. Up to 2 GHz, the same S_{21} general pattern can be observed in both measurements and simulations, even if a 10 to 100 MHz frequency shift is observed. Besides, it is interesting to observe that resonance peaks are present in both S_{21} simulations and measurements at longitudinal or vertical impedance resonance frequencies previously obtained in time and frequency domain. BPH longitudinal impedance resonances can be seen on Fig. 4 (1.08 GHz, 1.69 GHz and 1.88 GHz for instance, which are also observed in [9]), but others need a very close zoom and a smith chart to check that they indeed are resonances. This interesting observation also holds for the impedance resonances of the BPV, and leads to the conclusion that (1) the simulated BPM models are close to the real BPMs, and (2) indirect RF measurements without wire can give relevant information on a device's impedance.

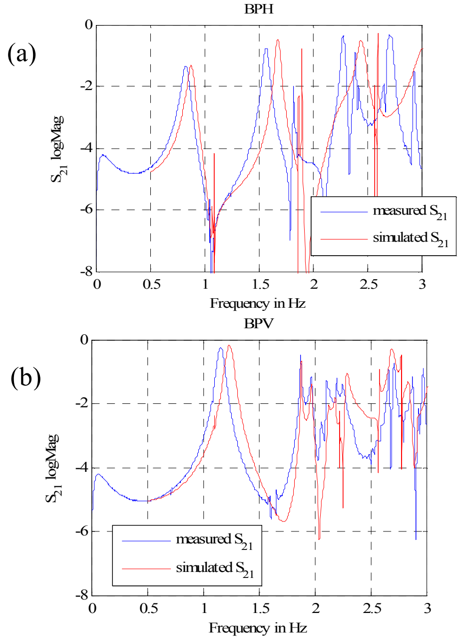

Figure 4: Comparison of Microwave Studio simulations (red) and RF bench measurements (blue) of the scattering parameter S_{21} for (a) the SPS BPH and (b) the SPS BPV. Up to 2 GHz, the general pattern is similar, but a frequency shift can be seen.

In order to improve the model, the small white ceramic spacers visible on the top of the electrode on Fig. 1(b) have been included in the simulations (see Fig. 5). As expected by waveguide theory [11], the ε_r=10 ceramic decreased the frequency of the modes, and improved the agreement between simulations and measurements.

CONCLUSION AND FUTURE WORK

The wake potentials for the SPS BPV and BPH were simulated in time domain with CST Particle Studio. For both the BPV and BPH, the impedance modes obtained from these time domain simulations were successfully benchmarked with frequency domain eigenmode simulations. The simulated model in general and the impedance mode frequencies in particular were also confirmed by non invasive bench RF measurements. Finally, although the total low frequency impedance of all SPS BPH and BPV is a small contribution to the total vertical and longitudinal impedance of the SPS machine (resp. 23 MΩ/m and 10 Ω in [12]), it will be important to check the effect of the trapped modes on the SPS beam.

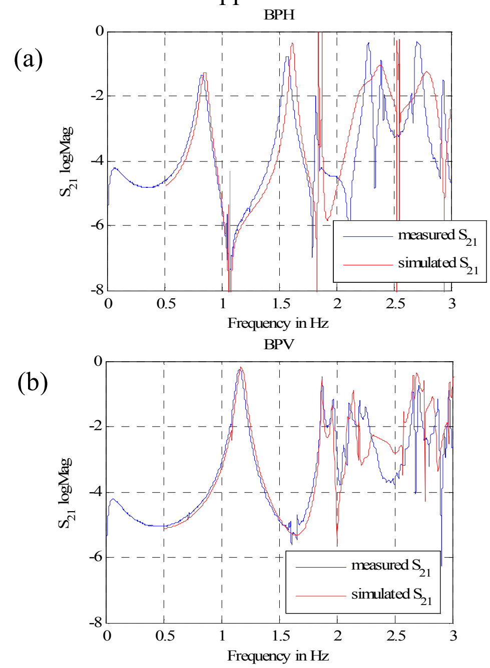

Figure 5: Microwave Studio simulations (red) and RF bench measurements (blue) of the scattering parameter S_{21} for (a) the SPS BPH and (b) the SPS BPV. Contrary to Fig. 4, the ceramics plots behind the electrodes were included in the simulations

ACKNOWLEDGMENTS

We would like to thank J. Albertone, M. Barnes, A. d'Elia, S. Federmann, F. Grespan, W. Höfle, E. Jensen, G. de Michele, Radiation Protection, and the AB-BT workshop for their help and advice!

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