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TRANSVERSE IMPEDANCE MODEL OF THE CERN-PSB

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Abstract

In the framework of the PS-Booster upgrade project an accurate impedance model is needed in order to determine the effect on the beam stability and assess the impact of the new devices before installation in the machine. This paper describes the PSB impedance model which includes resistive wall, indirect space charge, flanges, step transitions, ejection kicker including cables, injection kickers and cavities. Each impedance contribution has been computed for different energies in the PSB cycle. Measurements of the coherent tune shifts have been performed and compared to calculations based on the impedance model.

INTRODUCTION

A first attempt to build the PSB impedance model was made in the PhD thesis of D. Quatraro [1] where the attention was focused on the model of the wall impedance, which includes resistive wall and indirect space charge, and on the estimation of the so called "broadband impedance" (i.e. the measured impedance after the removal of the wall impedance) at different energies. These studies led to the conclusion that at injection about 50% of the measured tune shift can be attributed to indirect space charge and that the broadband impedance decreases with the relativistic beta. A more detailed impedance model of the PSB could help to explain the behavior of the measured tune shift at different energies. Presently, there is an ongoing effort to build such an impedance model and continuously refine it according to the modifications in the machine or new understanding.

PSB IMPEDANCE MODEL

The latest version of the impedance model includes resistive wall, indirect space charge, vacuum pipe discontinuities, ejection kicker including cables, injection kickers and FINEMET cavities. For each accelerator element the horizontal and vertical driving and detuning impedances have been calculated [2].

Indirect Space Charge

Up to now the indirect space charge impedance was estimated assuming the PSB to have an elliptic beam pipe (half height $h = 32$ mm and half width $w = 80$ mm) for 1/3 of the circumference, and a circular one for the remaining 2/3 (radius $r = 80$ mm) [1]. However, since the indirect space charge impedance is expected to play a major role, a more accurate calculation based on the PSB aperture model has been performed. For a circular chamber the indirect space charge impedance has been analytically calculated [3]. The calculation has been extended to the different PSB vacuum chambers by using the appropriate form factors [4], which have been numerically estimated with the simulation method for non-relativistic beta described in Ref. [5] for CST Particle Studio [6]. For the dipole chambers the form factors have been found very close to the rectangular chamber case [7], while a form factor of 1.4 has been estimated for the quadrupole chambers. More details on the PSB indirect space charge impedance model can be found in Ref. [4].

Table 1: Main parameters of the resistive wall calculation for the different vacuum chambers: thickness of the wall, electrical conductivity of the wall and background material.

	Wall thick [mm]	Wall (σ_{el}) [10^6S/m]	BG
Dipoles	0.4	0.77	Iron
Quadrupoles	1.5	1.3	Iron
Straight sections	1.0	1.3	Vacuum

Resistive Wall

In Ref. [1] the resistive wall impedance was estimated approximating the PSB elliptic beam pipe with a circular pipe with radius $r = h$, and considering the circular pipe for the rest of the accelerator. For the stainless steel an electrical conductivity $\sigma_{el} = 10^6$ S/m and a relative permeability $\mu_r = 8$ were used. Here we present a more accurate calculation based on the aperture model that accounts for the different PSB vacuum chambers. The calculation has been performed with the new code TLwall based on a transmission line model [2]. In Tab. 1 the main parameters used for the calculation are summarized. As an example, Fig. 1 shows the generalized horizontal and vertical resistive wall impedance of the PSB at kinetic energy of 160 MeV. The largest contribution to the resistive wall impedance is given by the bending magnets due to the very thin wall (0.4 mm). Due to the very thin layer, assuming an electrical conductivity of 7.7 10^5 S/m, the skin depth becomes larger than the wall thickness for frequencies below 2 MHz. Therefore, below this frequency the impedance becomes strongly dependent on the background material [4]. The iron has been modeled as a silicon-steel similarly to the SPS case [2]. The dispersion model for the permeability μ has been obtained as:

$$\mu = \mu_0\, \mu_r(\boldsymbol{B}) = \mu_0 (1 + \frac{\mu_i(\boldsymbol{B})}{1 + jf/f_{rel}}) \qquad (1)$$

with $f_{rel} = 10$ kHz [8]. The relative permeability μ_r is a function of the magnetic field $\boldsymbol{B}$ and thus of the particle momentum. The behaviour of μ_i as a function of $\boldsymbol{B}$ can be found in Ref. [9]. The variation of the resistive wall impedance due to the variation of μ_r during the PSB cycle has been estimated to be lower than 5%.

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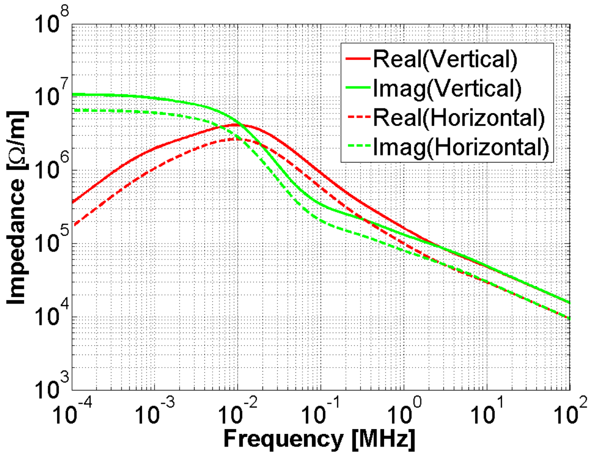

Figure 1: Vertical (full lines) and horizontal (dashed lines) generalized (driving+detuning) resistive wall impedance of the PSB at 160 MeV kinetic energy.

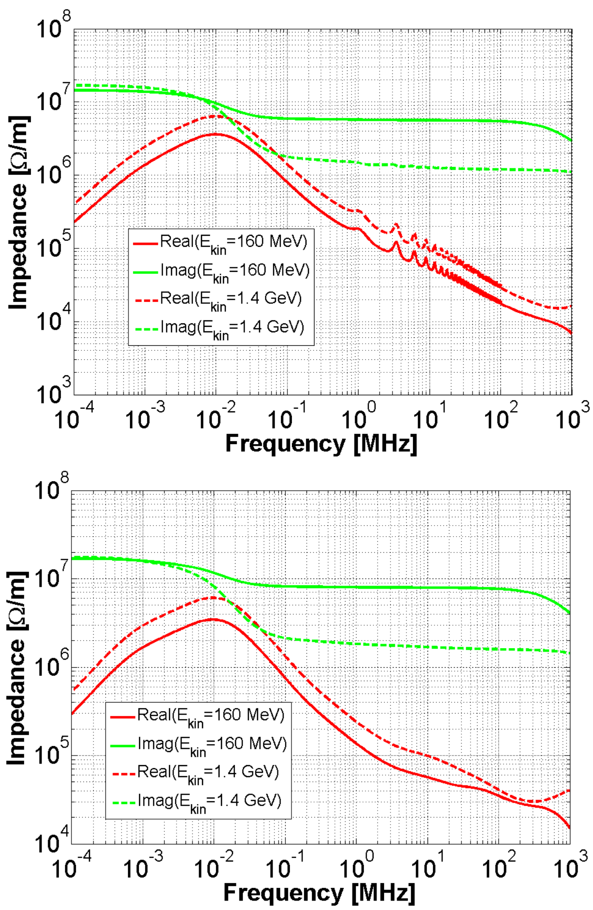

Figure 2: Total horizontal (top) and vertical (bottom) driving impedance of the PSB at 160 MeV and 1.4 GeV kinetic energy.

PSB Extraction Kicker

The contribution of the PSB extraction kicker has been estimated resorting to the theoretical model described in Refs. [2, 10]. The broadband impedance of the ferrite loaded structure is separated from the impedance due to the coupling to the external circuits. Due to the geometry of the kicker, the ferrite mainly determines the vertical impedance, while the external cable connections have an important impact on the horizontal impedance. The contribution due to the ferrite loaded structure is calculated by means of the Tsutsui model extended to the non-relativistic case [11,12]. The impedance due to the coupling to the external circuits has been obtained approximating the kicker as an ideal transformer [2, 10] placed in a transmission line with different terminations of the cables on either side (short-short, open-open, open-matched and open-short).

Vacuum Pipe Discontinuities

Based on the results of 3D EM simulations, for the PSB the broadband impedance contribution due to an abrupt transition can be considered independent of the relativistic beta. Therefore, based on the aperture model, the generalized broadband impedance of the PSB transitions has been calculated as:

$$Z_{transitions} = \sum_{i=1}^{N} Z_i \, n_i \qquad (2)$$

where N is the number of different transitions, Z_i is the broadband impedance of the transition i (β-weighted for the transverse impedance) and n_i is the number of occurrences of the transition i.

In circular accelerators with high acceleration rate the fast variation of the main magnetic field induces currents in the ground loop. To avoid that issue, the vacuum chamber is disconnected in several sectors and then reconnected with isolated flanges. From the circuital point of view, the isolated flange together with the ground loop can be modeled as a parallel RLC equivalent circuit [13]. To shift the resonant frequency of the equivalent RLC circuit to a much lower value and to reduce the beam coupling impedance, the so called RF-bypasses are connected in parallel to the flange. In the PSB all the flanges are equipped with RF bypasses; therefore, the impact of the PSB flanges on the global PSB impedance is expected to be negligible.

PSB Injection Kickers

The impedance contribution of the PSB injection kicker slow magnets (KSW) has been estimated by means of CST 3D simulations and analytical calculations of the resistive wall impedance based on the TLwall code [2]. Details about the impedance model of the KSW magnets can be found in Ref. [4].

FINEMET Cavities

Presently 10 FINEMET cavity cells are installed in the PSB ring 4. CST EM simulations based on the 3D model described in Ref. [14] indicate that the longitudinal beam coupling impedance of the Finemet cavities is weakly dependent on the relativistic beta. Therefore, the study that was done for the PS [14] should be representative also for the PSB. The transverse impedance model is based on CST simulations at different relativistic betas.

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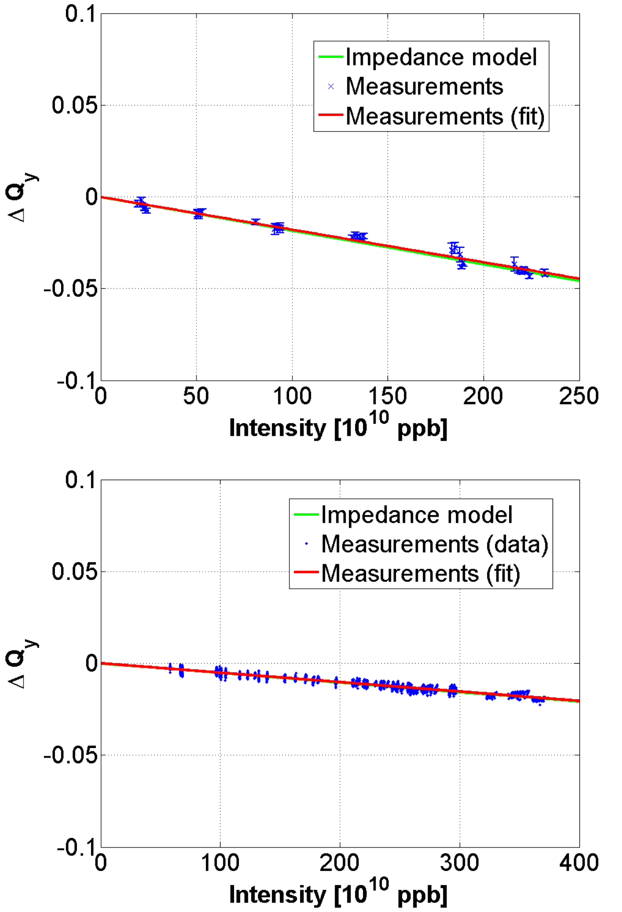

Figure 3: Comparison between the measured and expected (calculated from the impedance model [15]) vertical coherent tune shift at 60 MeV (top) and 160 MeV (bottom).

Global PSB Impedance Model

Figure 2 shows the full PSB impedance model including all the elements analysed weighted by the respective length and beta functions for the horizontal and vertical driving impedances. The contribution to the coherent tune shift of the different elements in terms of effective impedance for different energies has been summarized in Ref. [4].

COMPARISON WITH MEASUREMENTS

The measurements have been performed in all the PSB rings at 60 MeV, 160 MeV and 1.4 GeV. As expected, all rings have been found to give very similar tune shifts. In fact the FINEMET cavities, which are installed only in ring 4 are predicted to give a negligible contribution to the tune shift. The impedance model has been found to reproduce with good accuracy both the horizontal and vertical measured coherent tune shifts at 60 MeV and 160 MeV [4]. As example, Fig. 3 shows a comparison between the measured and expected vertical coherent tune shift at 60 MeV and 160 MeV. At these energies the coherent tune shift is dominated by the indirect space charge impedance contribution [4]. Therefore, the good agreement between measurements and predictions can be read as a benchmark of the indirect space charge impedance model. Some discrepancies (about 20%) have been observed at 1.4 GeV. At this energy, the indirect space charge impedance is expected to contribute to 1/3 of the tune shift [4]; therefore, a significant contribution comes also from other impedance sources. The measurements at 1.4 GeV seem to indicate that the impedance coming from other sources is slightly underestimated.

CONCLUSIONS

The present PSB impedance model has been found to reproduce the horizontal and vertical coherent tune shifts at energies where the indirect space charge impedance is dominant (60 MeV and 160 MeV). On the other hand, the model gives a 20% smaller tune shift at 1.4 GeV where the indirect space charge impedance contribution to the tune shift is not dominant anymore. Therefore, the impedance coming from other sources is underestimated.

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