

THE PROTON SYNCHROTRON TRANSVERSE IMPEDANCE MODEL

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Abstract

The current knowledge of the transverse impedance of the CERN Proton Synchrotron (PS) has been established by theoretical computations, electromagnetic simulations and beam-based measurements at different energies. The transverse coherent tune and phase advance shifts as a function of intensity have been measured in order to evaluate the total effective transverse impedance and its distribution in the accelerator. In order to understand the beam dynamics, the frequency dependence of the impedance budget has also been evaluated considering the individual contribution of several machine devices. 3D models of many PS elements have been realized to perform accurate impedance simulations, while resistive wall and indirect space charge impedances have been evaluated with theoretical and numerical computations. Finally comparisons between the total budget and the measurement results are presented.

INTRODUCTION

The CERN PS belongs to the LHC injector chain, accelerating protons coming from the PS Booster from 1.4 GeV to 25 GeV (kinetic energies). It has a fundamental role in the accelerator complex, injecting high intensity and brightness beams in the Super Proton Synchrotron for collision in the LHC. Coupling impedance and wake fields describe the electromagnetic interaction of a particle beam with the surrounding environment; interacting with the motion of trailing particles, they lead to undesired effects like energy loss, beam instabilities, and beam-induced heating. For the future operation at higher intensities and beam brightness required by the LIU project [1], it is of fundamental importance to detect the main sources of impedance in the machine and estimate with some precision the transverse impedance model. At the moment some transverse instabilities that, kept under control, are not dangerous for the operation, have been observed in the machine: for example, the transverse damper currently installed in the PS is sufficient to damp the injection instabilities, and transition crossing should also be possible without major issues. However, a careful follow-up of the transverse impedance of the machine allows the possibility to accelerate high-intensity beams with lower longitudinal emittance through transition, and to minimize the interplay with space charge at injection energy.

COHERENT TRANSVERSE TUNE SHIFT MEASUREMENTS

For a Gaussian bunch of r.m.s. bunch length σ_z and velocity $v = \beta c$, the coherent tune shift ΔQ is proportional

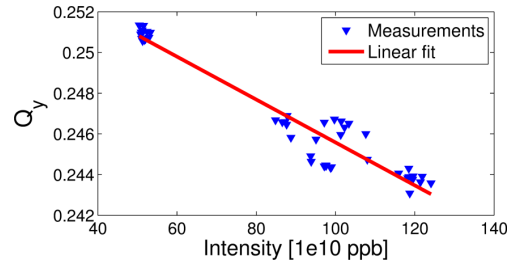


Figure 1: Measurements of vertical tune shift at 2 GeV.

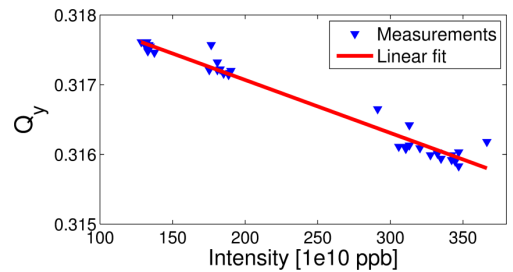


Figure 2: Measurements of vertical tune shift at 25 GeV.

to the imaginary part of the transverse effective impedance Z_t^{eff} by [2]

$$\Delta Q = -\frac{\beta e I_0}{4\sigma_z \sqrt{\pi} \omega_0^2 \gamma Q_0 m_0} \text{Im}[Z_t^{eff}], \quad (1)$$

where I_0 is the bunch current, Q_0 is the zero current betatron tune, γ is the relativistic factor, e the particle charge, ω_0 the angular revolution frequency and m_0 the particle mass at rest. The transverse effective impedance is defined as

$$Z_t^{eff} = \frac{\sum_{p=-\infty}^{\infty} Z_t(\omega') h(\omega' - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h(\omega' - \omega_\xi)}, \quad (2)$$

where $\omega' = \omega_0(p + Q_0)$ with p an integer, $\omega_\xi = \omega_0 Q_0 \xi/\eta$, with ξ the chromaticity and η the slippage factor, and the power spectrum of the Gaussian zero azimuthal bunch mode is $h(\omega) = \exp(-\omega^2 \sigma_z^2/c^2)$. If the bunch length does not change with intensity, Eq. 1 predicts a tune shift linear with bunch current, with a slope proportional to the imaginary part of the transverse total effective impedance. Transverse coherent tune shifts measurements at PS injection (1.4 GeV), close to transition (2 GeV) and extraction (25 GeV) have been performed. In Fig. 1 and 2 two examples of the measured tune shift on the vertical plane at 2 GeV and 25 GeV are shown. Bunch lengths of 94 ns and 53 ns have been considered for the measurements at 2 GeV and 25 GeV, respectively.

Results from measurements, performed during machine development studies in 2012-2013, show a vertical effective impedance of 9.6 M Ω /m at kinetic energy of 2 GeV, and

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Table 1: Indirect space charge contributions to the total vertical effective impedance at different kinetic energies for round chamber and parallel plates.

Energy	1.4 GeV	2 GeV	25 GeV
Flat	6.0 MΩ/m	3.7 MΩ/m	<0.5 MΩ/m
Round r=35 mm	4.9 MΩ/m	3.0 MΩ/m	<0.5 MΩ/m

4.5 MΩ/m at kinetic energy of 25 GeV. Only results of the effective vertical impedance are reported in this paper. Other tune shift measurements at different energies are planned for the 2014 machine development sessions.

TRANSVERSE IMPEDANCE CALCULATIONS

Indirect Space Charge

The observed difference in the effective impedance in the vertical plane between these two sets of measurements can be explained by the effect of the coherent indirect space charge, induced by a beam inside a perfectly conducting infinitely smooth beam pipe. If we approximate the PS elliptic beam chamber as two parallel plates, indirect space charge contribution to the imaginary part of the total effective vertical impedance is 6 MΩ/m at 1.4 GeV and 3.7 MΩ/m at 2 GeV. If we consider a round chamber of 35 mm radius, we get 4.9 MΩ/m and 3 MΩ/m for the two energies. At 25 GeV, the contribution to the impedance of the coherent indirect space charge becomes negligible. In Table 1 the results of the indirect space charge contributions are summarized. We expect that the parallel plates and the round chamber give a good approximation for the vertical plane.

Resistive Wall

A machine made of stainless steel 316 LN (about 70% of the total length) and of Inconel X750 alloy (about 20%) has been considered for resistive wall calculation [3]. Both a round chamber model (35 mm radius) and parallel plates model have been taken into account. The transverse effective impedance obtained is very close for the two geometries: 0.29 MΩ/m for the round chamber and 0.35 MΩ/m for a parallel plates model. For the parallel plates, on the vertical plane, the dipolar and quadrupolar impedance contributions are of same sign: the total vertical impedance is therefore increased by a factor 1.2 with respect to the round chamber case. Instead, on the horizontal plane, the parallel plates model gives zero total impedance due to the perfect compensation of dipolar and quadrupolar components of the impedance.

Kicker Magnets

Kicker magnets are predicted to be an important source of impedance in the PS. CST Particle Studio [4] simulations, and calculation with the Tsutsui theoretical formula, have been performed for all the PS kickers, showing very good agreement in the transverse and longitudinal plane [5]. An

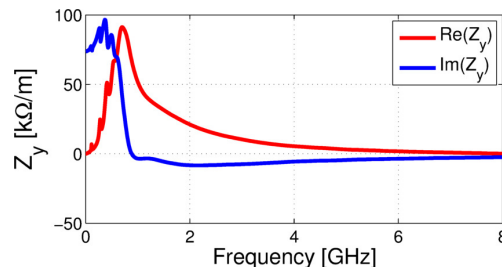


Figure 3: Kicker KFA13 vertical dipolar impedance calculated with CST Particle Studio.

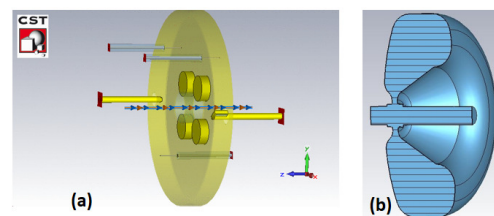


Figure 4: CST 3D models of the 200 MHz (a) and 80 MHz (b) cavities used for simulations.

example of the dipolar vertical impedance calculated with CST for kicker KFA13 is shown in Fig. 3. A comparison between simulation and measurement has also been done for the kicker KFA13 [6], revealing a good agreement, in particular on the vertical plane. Summing the total imaginary part of the transverse impedance (dipolar and quadrupolar contribution) obtained with CST Particle Studio for all the PS kickers, we obtain that their contribution to the machine impedance budget, at the energy of 2 GeV, is less than 0.03 MΩ/m in the horizontal plane, and about 1.4 MΩ/m in the vertical plane. Kickers magnets can explain about the 15% of the vertical impedance measured at 2 GeV.

RF Cavities

Electromagnetic computations with the 2D code ABCI [7] and with the 3D code CST Particle Studio have been performed for the PS RF cavities. The current impedance budget includes the contribution of the 10 MHz, 40 MHz, 80 MHz (Fig. 4 on the right) and the 200 MHz complex (Fig. 4 on the left). Results from simulations show that RF cavities do not have a strong impact on the transverse impedance and they can explain less than 1% of the vertical impedance measured at 2 GeV. The imaginary part of the vertical impedance for the 10 MHz cavities and the 200 MHz complex is shown in Fig. 5. As an output of the impedance studies, 3D models are currently available for the first time for all PS cavities.

Vacuum Equipment

Vacuum equipment and features in the PS beam line like pumps, sector valves, bellows, steps and misalignments are included in the model as distributed elements. Currently the impedance budget includes the contribution of 100 vacuum pumps, 10 sector valves (Fig. 6 right), about 200 bellows (Fig. 6 left) and 60 step transitions between elliptical and

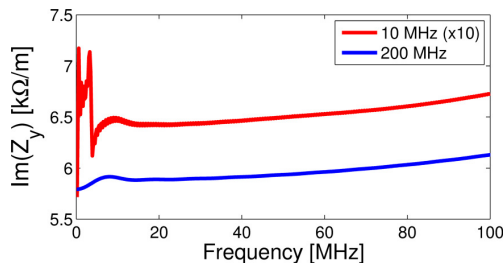


Figure 5: Plot of the imaginary part of the vertical dipolar impedance simulated with CST Particle Studio for the 200 MHz complex (blue line) and the ten 10 MHz cavities (red line).

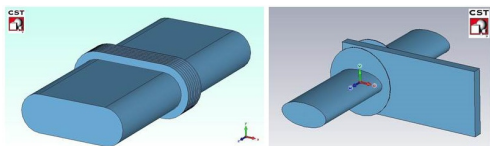


Figure 6: CST 3D models of a beam line section with bellow (left) and a sector valve (right).

circular chambers. Even if the impedance of the single element is predicted to be small, the sum of many distributed elements can explain about 5% of the vertical impedance measured at 2 GeV.

TOTAL TRANSVERSE IMPEDANCE BUDGET

The purpose of the study is to obtain an impedance budget that could explain the results from beam based measurements, summing the transverse impedances of each machine element calculated analytically and with electromagnetic simulations: in this way we assess the frequency dependence of the total machine impedance. If we consider the vertical budget calculated at 2 GeV, we can compare results with the measured effective vertical impedance, that is about 9.6 MΩ/m. Summing together the imaginary part of the vertical impedances for each machine elements, and weighting them with beta functions defined in the lattice, we obtained the curves plotted in Fig. 7. The envelope of the red area represents the sum of the imaginary part of the impedance curves of our estimation. In this example, about 60-70% of the vertical impedance measured at 2 GeV is explained. The study is ongoing: several elements (wire scanners, pickups, septa, flanges) are going to be added to the current budget, and impedance localization measurements [8] are planned for the machine development studies in 2014. The current budget also includes several new elements installed in the machine during the Long Shutdown 2013-2014 [9, 10].

CONCLUSIONS

In this work we presented the results of transverse impedance study for the PS taking into account several machine elements. The curves of the imaginary part of the

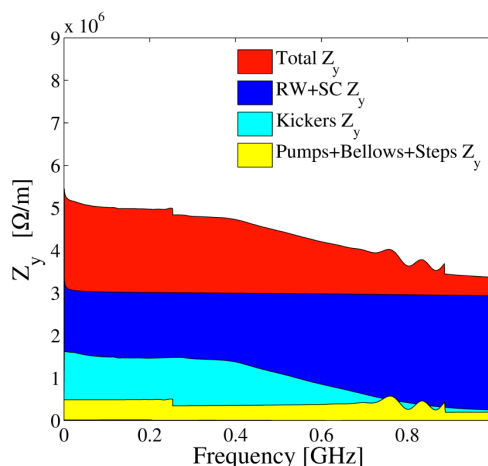


Figure 7: Frequency dependence of the imaginary part of the total vertical (dipolar and quadrupolar component) impedance budget calculated at 2 GeV.

transverse impedance have been summed in order to assess the total frequency dependence of the impedance budget. The budget is then compared to results from tune shift measurements: about the 60-70% of the vertical impedance measured at 2 GeV is explained. The study is ongoing: several elements are going to be added to the current budget.

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