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CERN SPS IMPEDANCE IN 2007

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Abstract

Each year several measurements of the beam coupling impedance are performed in both longitudinal and transverse planes of the CERN Super Proton Synchrotron to keep track of its evolution. In parallel, after the extensive and successful campaign of identification, classification and cure of the possible sources of (mainly longitudinal) impedance between 1998 and 2001, a new campaign (essentially for the transverse impedance this time) has started few years ago, in view of the operation of the SPS with higher intensity for the LHC luminosity upgrade. The present paper summarizes the results obtained from the measurements performed over the last few years and compares them to our predictions. In particular, it reveals that the longitudinal impedance is reasonably well understood and the main contributors have already been identified. However, the situation is quite different in the transverse plane: albeit the relative evolution of the transverse impedance over the last few years can be well explained by the introduction of the nine MKE kickers necessary for beam extraction towards the LHC, significant contributors to the SPS transverse impedance have not been identified yet.

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Each year several measurements of the beam coupling impedance are performed in both longitudinal and transverse planes of the CERN Super Proton Synchrotron to keep track of its evolution. In parallel, after the extensive and successful campaign of identification, classification and cure of the possible sources of (mainly longitudinal) impedance between 1998 and 2001, a new campaign (essentially for the transverse impedance this time) has started few years ago, in view of the operation of the SPS with higher intensity for the LHC luminosity upgrade. The present paper summarizes the results obtained from the measurements performed over the last few years and compares them to our predictions. In particular, it reveals that the longitudinal impedance is reasonably well understood and the main contributors have already been identified. However, the situation is quite different in the transverse plane: albeit the relative evolution of the transverse impedance over the last few years can be well explained by the introduction of the nine MKE kickers necessary for beam extraction towards the LHC, significant contributors to the SPS transverse impedance have not been identified yet.

INTRODUCTION

The impedance reduction program, which took place between 1999 and 2001, revealed an impedance reduction factor of ~ 2.5 in the longitudinal plane and ~ 0.4 in the vertical one (See [1] and references therein). Since then, in order to extract the beam towards the LHC, new extraction kickers (MKE) were installed: five in 2003 (leading to a total of 16 kickers), and four in 2006 (leading to a total of 20 kickers). Note that one of the MKE kicker was shielded on 2 cells. In 2007 one MKE kicker was removed and one MKE was "fully" shielded, leading to a total of 19 kickers.

To be able to follow the impedance increase and its impact on the beam dynamics, systematic beam-based impedance measurements were performed over the last few years. The aim of the present paper is to summarize the main results and to compare them to our predictions. The outline is the following: the first section deals with the vertical coherent tune shift vs. intensity. The second section is devoted to the study of the Transverse Mode-Coupling Instability (TMCI) at injection. In the third section, head-tail growth/decay rate measurements vs. chromaticity are discussed, while in the fourth section the results of the localization of the vertical impedances from measurements of the betatron phase-beating vs. intensity are analyzed. Finally the longitudinal impedance is addressed in the fifth section from measurements of the quadrupole synchrotron frequency shift with intensity.

VERTICAL COHERENT TUNE SHIFT

The measurements of the single-bunch vertical coherent tune shift vs. intensity are depicted in Fig. 1. It can be first seen that in 2001 the measured "total" (i.e. dipolar plus quadrupolar) effective impedance was reduced by 40% compared to the measured value in 2000. Secondly, one can observe that the measured "total" impedance increase from 2001 to 2006 (i.e. due to the installation of the 9 MKE kickers) is 4.5 MΩ/m, which has to be compared to 5.2 MΩ/m expected from theory (see Table 1). Furthermore, a slight reduction of the impedance was expected in 2007 (due to the removal of one MKE kicker and shielding of another one). This seems also to be reflected in Fig. 1, even though one might reach the precision limit for the measurements and the exact predicted "total" impedance of the shielded kicker could not be given as the quadrupolar impedance is missing (only the dipolar impedance was measured). This good agreement reveals that the impact of the hardware modifications can be reasonably well explained since 2001. Note that the imaginary part of the vertical effective dipolar impedance of the shielded kicker is $\mathrm{Im}[Z_{y,dip}]_{eff} = 0.24$ MΩ/m, whereas it was 0.27 MΩ/m

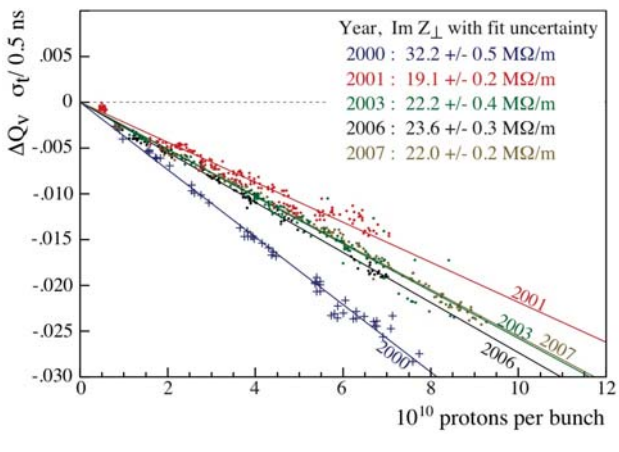

Figure 1: Measurements of the single-bunch vertical coherent tune shift vs. intensity over the last years.

before the shielding, revealing a small effect of the shielding in the vertical plane. Furthermore, the imaginary part of the vertical effective "total" impedance from space charge (which contributes to the coherent tune shift) is $\mathrm{Im}[Z_y]_{eff} = 2.6$ MΩ/m.

The conclusions of these measurements are that (i) the contribution from all the kickers vs. time can be reasonably well explained, (ii) all the kickers in 2006 (and 2007) contribute to ~ 40 % of the total measured impedance and (iii) 13 MΩ/m are still missing.

Table 1: Summary and comparison between measurements (of the whole SPS) and theoretical predictions (using only the contribution of the kickers).

$\mathrm{Im}(Z_y)_{eff}$ [MΩ/m]	Meas	delta	Theory (kickers)	delta	Error delta [%]
2001	19.1		3.5		
2003	22.2	3.1	6.4	2.9	7
2006	23.6	1.4	8.7	2.3	-39
2007	22	-1.6			

TMCI AT INJECTION

This subject is discussed in detail in Ref. [2]. The main results are that a double instability threshold and a tune step were observed on both tracking simulations (using the impedance of the kickers) and on SPS experiments performed in 2007. These mechanisms can both be explained by a first regime of mode coupling-decoupling (leading a small instability) followed by the main mode-coupling (leading to the fast instability). The simulated (main) intensity threshold is ~ 9.3 10^{10} p/b, while ~ 7.6 10^{10} p/b were measured (see Fig. 2), which leads to an already quite good agreement (~ 20 %).

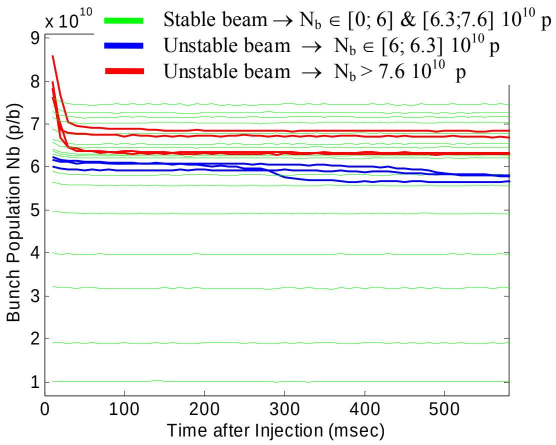

Figure 2: Bunch intensity vs. time for a bunch with low longitudinal emittance ($\varepsilon_L = 0.16$ eVs).

HEAD-TAIL GROWTH/DECAY RATE

Changing the (vertical) chromaticity the growth or decay rates of the single-bunch head-tail instability can be measured. This provides information about the real part of the vertical impedance (see Fig. 3). The conclusion from these measurements is that the real part of the effective vertical impedance from all the (20) kickers in 2006 contribute to ~ 50% of the total measured impedance. A more precise comparison will be performed with the improved impedance model used in Ref. [2].

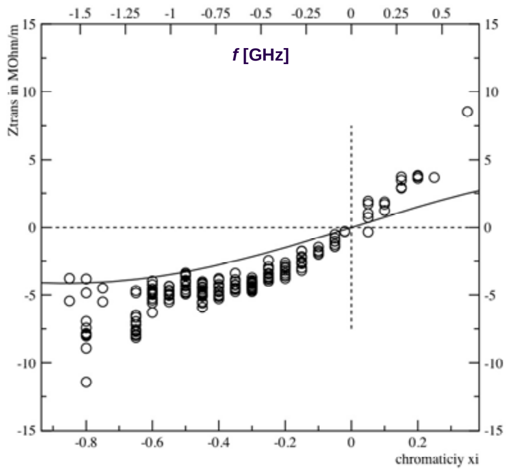

Figure 3: Comparison between the measured (dots) and computed (full black curve) real part of the effective vertical impedance vs. chromaticity.

IMPEDANCE LOCALIZATION

An effort to localize the vertical impedance sources in the SPS was carried out using beam based techniques as proposed in Ref. [3]. Simulations using the HEADTAIL code [4] were performed to understand the effectiveness of this technique and the imposed constraints. The analysis from HEADTAIL, using as source impedances only the SPS kickers, indicates that: (i) all focusing and defocusing quadrupoles when used as variables in response matrix correction are able to approximately reconstruct the source location without any constraints, (ii) the amplitude and transverse orientation of the impedance source cannot be easily inferred from a quadrupole response matrix. More advanced choice of the

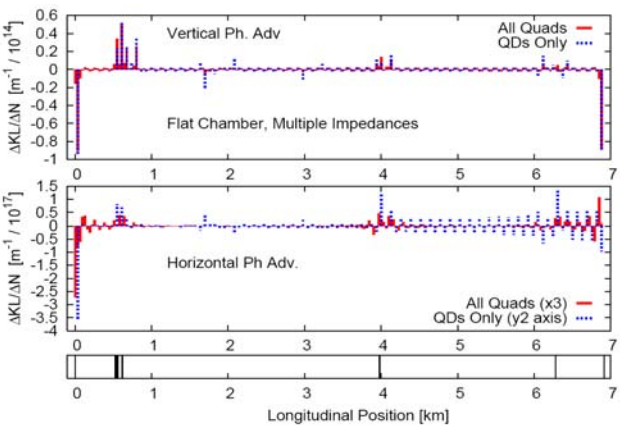

Figure 4: Local impedance distribution around the SPS ring from the simulated (with HEADTAIL) current-dependent phase beating at 26 GeV/c, considering all the kickers only (whose position is shown in the lower plot).

variable vector space and algorithms maybe help improve the solution, (iii) effects of noise and faulty BPMs are under investigation to define the confidence level of the localization with real data. Analysis of SPS data based on the developments from HEADTAIL simulation are underway.

QUADRUPOLE FREQUENCY SHIFT

The inductive part of the effective longitudinal impedance can be assessed by measuring the quadrupole oscillation synchrotron frequency shift vs. intensity. The results of these measurements over the last years can be found in Fig. 5. It can be first seen that in 2001 the measured effective impedance was reduced by a factor of ~ 2.5 compared to the measured value in 1999. Secondly, one can observe that the effective impedance increase from 2001 to 2006 (i.e. due to the installation of the 9 MKE kickers) is 3 Ω, which has to be compared to 4 Ω expected from theory (see Table 2). A slight reduction of the impedance was expected in 2007 (due to the removal of one MKE kicker and shielding of another one). Contrary to the expectations first measurements in 2007 revealed an increase of the impedance by ~ 40 %. More measurements were performed at the end of the 2007 run, where the result of 2006 was recovered. The conclusions from these measurements are that (i) the contribution from all the kickers vs. time can be reasonably well explained until 2006/2007, (ii) depending on the bunch length and longitudinal emittance, huge differences can be observed (as expected) [5].

Note that the longitudinal effective inductive impedance of the shielded kicker is $Im[Z_l/n]_{eff} = 0.1$ Ω, whereas it was 0.4 Ω before the shielding, which reveals the important effect of the shielding. Furthermore, the longitudinal effective inductive impedance from space charge is $Im[Z_l/n]_{eff} \approx -1$ Ω, and it has already been subtracted from the above cited numbers.

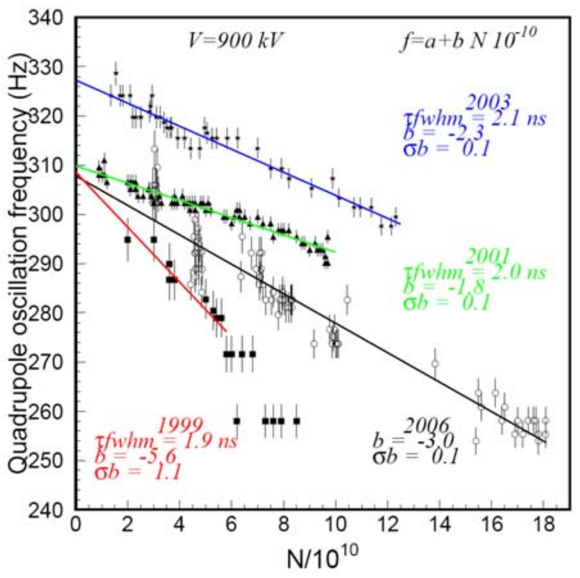

Figure 5: Quadrupole synchrotron frequency vs. intensity from 1999 to 2006.

Table 2: Summary and comparison between measurements (of the whole SPS) and theoretical predictions (using only the contribution of the kickers).

$Im(Z_l/n)_{eff}$ [Ω]	Meas	delta	Theory (kickers)	delta	Error delta [%]
2001	4.4		1.2		
2003	6.2	1.8	3.4	2.2	-18
2006	7.4	1.2	5.2	1.8	-33
2007	10.2	2.8	4.4	-0.8	-450

CONCLUSION

Although a relatively good agreement is obtained when relative values are discussed, the kickers can only explain ~ 40% (9.4 MΩ/m deduced from simulations in Ref. [2]) of the vertical impedance measured from vertical coherent tune shift. Removing the contribution from space charge to the coherent tune shift, ~ 13 MΩ/m are still unexplained. The vertical impedance of several other equipments has been computed or simulated, but it is negligible compared to the missing impedance [1]. The next steps will consist in: (i) adding all the impedances of the simulated equipments into ZBASE [6] and (ii) continuing the identification of additional sources.

The head-tail growth/decay rate measurements also confirm that ~ 50% of the vertical impedance is still unexplained, whereas a better agreement (~ 20%) seems to be obtained from TMCI studies [2].

In the longitudinal plane, the agreement is relatively good (when both relative and absolute values are discussed) as the main remaining part, ~ 3.2 Ω (= 4.4 Ω – 1.2 Ω) in 2001, could be mainly explained by the RF cavities [1]. In the future more time should be devoted to study the HOMs responsible for the (quite low) longitudinal coupled-bunch instability threshold.

Finally, the fact that the quadrupole synchrotron frequency shift was not very well determined during first measurements in 2007 was attributed to the lack of reproducibility of bunch length and emittance at injection [5]. In the future more attention should be paid to make these parameters reproducible.

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