ANALYSIS OF THE TRANSVERSE SPS BEAM COUPLING IMPEDANCE WITH SHORT AND LONG BUNCHES

B. Salvant (EPFL and CERN, Switzerland), R. Calaga, R. de Maria (BNL, NY, USA), G. Arduini, H. Burkhardt, H. Damerau, W. Höfle, E. Métral, G. Papotti, G. Rumolo, R. Tomas, S. White (CERN, Geneva)

Abstract

The upgrade of the CERN Large Hadron Collider (LHC) would require a four- to fivefold increase of the single bunch intensity presently obtained in the Super Proton Synchrotron (SPS). Operating at such high single bunch intensities requires a detailed knowledge of the sources of SPS beam coupling impedance, so that longitudinal and transverse impedance reduction campaigns can be planned and performed effectively if needed. In this paper, the transverse impedance of the SPS is studied by injecting a single long bunch into the SPS, and observing its decay without RF. Longer bunches allow for higher frequency resolution of the longitudinal and transverse bunch spectra acquired with strip line couplers connected to a fast data acquisition. It also gives access to the frequency content of the transverse impedance. Results from measurements with short and long bunches in the SPS performed in 2008 are compared with simulations.

INTRODUCTION

Dedicated SPS machine studies have been carried out to estimate the longitudinal and transverse impedance and identify the main impedance contributors. Among the techniques used to obtain information on the SPS impedance [1,2], one can measure the quadrupolar oscillation frequency shift and bunch lengthening with intensity, the power loss, instability thresholds, betatron tune shifts with intensity, growth and decay rate with chromaticity, or localize the sources of impedance. Finally, dedicated measurements have taken place to get more information on the frequency content of the SPS longitudinal and transverse impedance [3]. In the latter method, the longitudinal spectrum of slow debunching long bunches in the SPS was measured and provided information on longitudinal resonant impedances.

In this contribution, latest comparisons between short bunch measurements and simulations are reported, as well as attempts to take advantage of high-sampling rate oscilloscopes to measure the transverse bunch spectrum.

SIMULATIONS AND MEASUREMENTS FOR SHORT BUNCHES

Wake functions calculated from SPS beam pipe and SPS kickers theoretical models were added to wake functions obtained from electromagnetic simulations of SPS horizontal and vertical Beam Position Monitors (BPHs and BPVs), hence obtaining dipolar and quadrupolar wake functions, which were used as inputs of Headtail macroparticle simulations [4]. The evolution of the main line of the vertical tune spectrum for dedicated machine studies (described in detail in [5]) and simulations is presented in Fig. 1. The simulations predict a "tune shift with intensity" 40% smaller than the measurements, but predict an instability threshold close to the measurement (7.4 10^{10} protons instead of 7.5 10^{10}). These differences can be attributed to the extra impedance contributions not yet included in the model. In addition the model of the kickers could be further improved by electromagnetic simulations. Also, the direct space charge was not included in these simulations and it should increase significantly the threshold. Finally, the shape of the tune spectrum remains similar to that of reference [5], indicating a coupling between transverse modes -2 and -3.

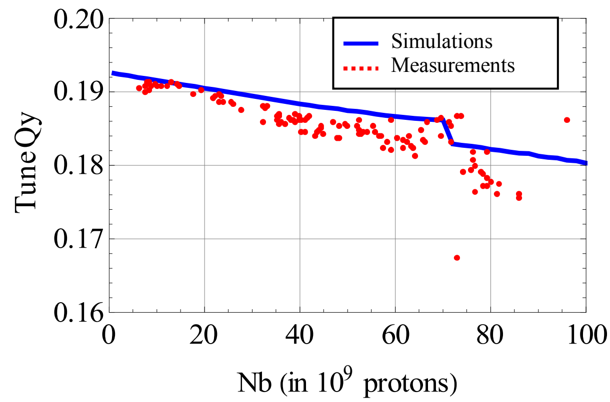

Figure 1: Comparison of bunch stronger vertical mode (Q_y) vs. bunch population (Nb). SPS experiment and Headtail simulations for 2006 SPS kickers, beam pipe, BPHs and BPVs. Parameters: longitudinal emittance ε_L=0.16 eV.s, RF Voltage V_{RF} = 1 MV, chromaticity $\xi \sim 0$, rms bunch length σ_t = 0.7 ns (measurement) and σ_t=0.5 ns (simulations). The simulated tune data was translated and normalized by the experimental bunch length data to be able to compare the tune slope.

SIMULATIONS AND MEASUREMENTS WITH DEBUNCHING LONG BUNCHES

Headtail Macroparticle Simulations

Initiated by the success of the method in the longitudinal plane [3], an attempt was made to obtain more information on the frequency spectrum of the transverse impedance by observing the frequency spectrum of a debunching bunch subject to a vertical instability at SPS injection (relativistic gamma γ=27.7). *Headtail* simulations of a long debunching single bunch (N_b=2 10^{11} protons, σ_t=3.5 nsec, ε_l=0.15eVs) interacting with a classically used broadband impedance model for the SPS (Q=1, f_{res}=1.3GHz, R_s=7.6 MΩ/m for the dipolar contribution, the quadrupolar contribution is found from the form factors for a flat chamber, as explained for the models of the kickers in [1]) show that the vertical coherent motion gets unstable after around 200 turns (see Fig. 2). A frequency analysis of the turn by turn coherent vertical motion reveals a strong resonant mode around 1.15 GHz, which is is consistent with the effective frequency of a broadband resonator $f_{res} = \sqrt{1-1/4Q^2}$. This mode is however observed to shift towards low frequencies as the number of turns increases. Also, another significant mode or group of modes grows and shifts from low frequencies towards 500 MHz.

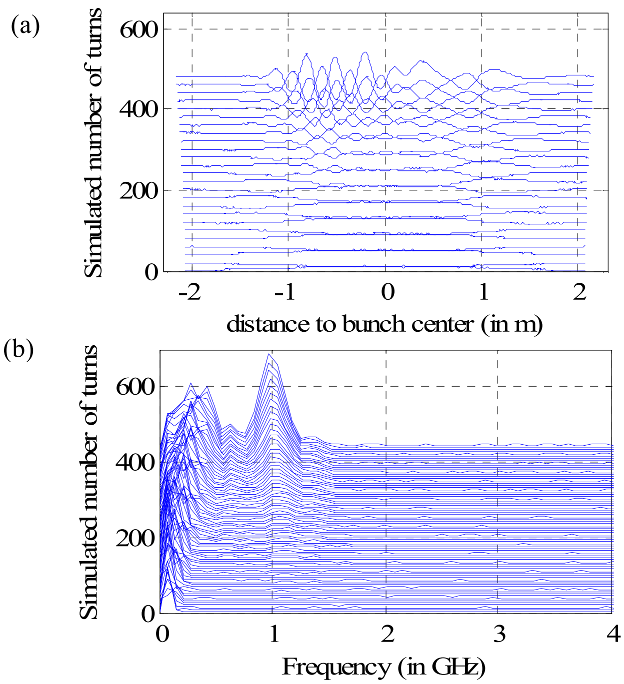

Figure 2: Mountain range frequency spectrum of the simulated vertical delta signals of long debunching bunch interacting with dipolar and quadrupolar contributions of a broadband impedance (flat pipe).

An improved model that includes the resistive wall impedance contributions from all kickers of the SPS is now used for simulations assuming the same initial long bunch as in Fig. 2 [1]. With this model, the dipolar wake function is close to that of a flat chamber broadband model (Q=0.6, f_{res}=2.3 GHz, R_s=3.5 MΩ/m). The mountain range of the simulated delta signals and frequency spectra obtained with the resistive wall model are shown in Fig. 3. An oscillation is observed, but its resonance frequency is much lower than the frequency of the maximum of the kicker impedance spectrum (500 MHz instead of 2.3 GHz [1]). This resonance has a similar dynamic behaviour as the resonance that starts from low frequencies in Fig. 2, and is the only one observed, even with a much higher number of turns. In this case close to a resonator with lower impedance and quality factor, the delta signal does not give useful information on the frequency spectrum of the transverse impedance.

Although *Headtail* simulations with a Q=1 broadband impedance model encourage to perform SPS measurements with long bunches to assess the frequency spectrum of the transverse SPS impedance, simulations with a more accurate model of the SPS kickers suggest that the obtained spectrum may not trivial to interpret. Besides the number of turns needed to obtain a clear frequency spectrum may be too large for real measurements with lower bunch populations, since unavoidable damping terms and longitudinal impedance will complicate the spectrum.

In the future, further simulations could be performed with a combination of high Q and low Q resonators (such as the model that includes the SPS BPMs in [4]) to see if the delta signal would provide more information.

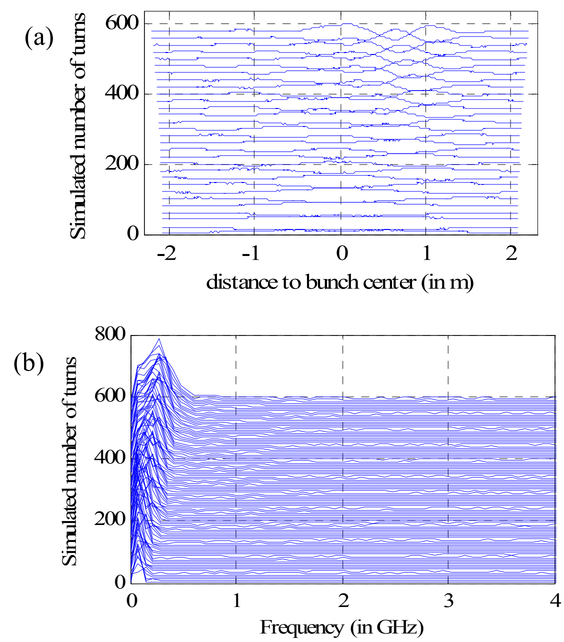

Figure 3: Mountain range of the time domain (a) and frequency domain (b) simulated delta signals of a long debunching bunch interacting with a the resistive wall model of the SPS kickers impedance.

Measurements with the SPS Beam

Bunches with tightly controlled longitudinal emittance and varying intensity were produced in the PS complex for the dedicated studies in the SPS. Longer bunches were obtained by adiabatically decreasing the RF voltage in the PS before extraction to the SPS. Additionally, a bunch rotation, normally used to shorten bunches before extraction was disabled. Bunches of 11 ns, 16 ns and 20 ns ($4\sigma_t$) length could be obtained, depending on the RF voltage at extraction. However, the longitudinal profile of the 20 ns long bunches was observed to be distorted.

As for the studies in Ref. [4], the long bunches were injected into the SPS with the RF cavities turned off, and both the wall current monitor and a vertical wideband directional coupler (BPW 31901) [6] connected to high sampling rate oscilloscopes (20 and 40 GS/sec) were used to observe the delta and sum signals. An example of the delta and sum signals for a bunch of $Nb=10^{11}$ protons $4\sigma_t$=11 ns (transversally unstable) is illustrated in Fig. 4. The reversed exponential pick-up and cable transfer functions were applied to the time domain sum and delta signals. As in [3], the sum (longitudinal) spectrum is affected by resonances at the fundamental frequency of the 200 MHz cavities and its harmonics from 300 turns after injection onwards.

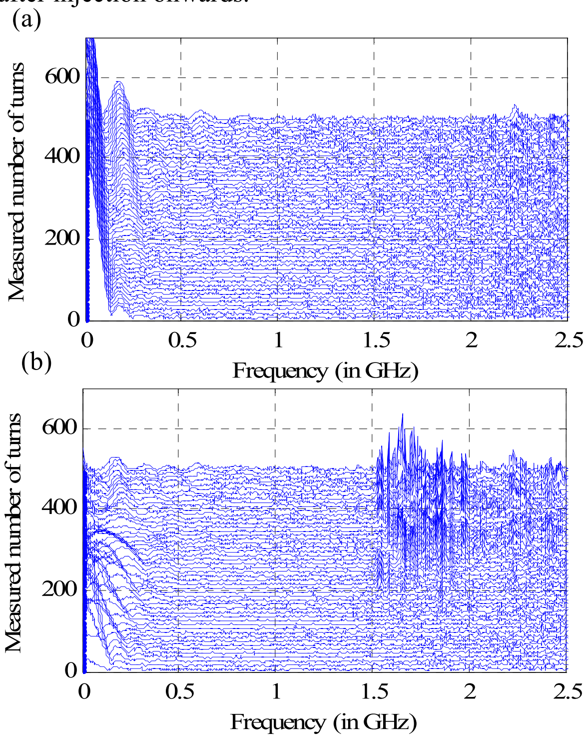

Figure 4: turn-by-turn mountain range of the measured sum (a) and delta (b) frequency spectra of a long unstable debunching bunch in the SPS measured with BPW 31901.

The delta (transverse position*sum) spectrum shows an expansion of the activity in the low frequency similar to the simulated spectrum for the kickers up to 300 turns. After 300 turns, this activity suddenly stops and the spectrum shows the RF cavities resonances as in the longitudinal plane, but a strong activity appears between 1.6 and 2 GHz. It is known [6] that in this frequency range the beam pipe that houses the transverse wideband (BPW) pick-ups starts supporting the propagation of electromagnetic modes. In fact the TE_{11} mode cut-off frequency is at 1.64 GHz and very close to the lower boundary of the observed signal. As it is a transverse mode the signal will pre-dominantely show-up in the difference signal from this pick-up and approximately cancels in the sum signal. On the one hand the pick-up response is no longer flat in the region beyond the cut-off frequency, and it is difficult to judge to what extent the observed activity is due to a real bam instability or a result of a "ringing" in the pick-up response due to the bunches that become shorter. On the other hand the relative clean signals before turn 300 suggest that the signal is indeed related to an activity on the beam, the relevance for the machine impedance however needs further assessment. In conclusion, no strong vertical activity was observed, in particular between 500 MHz and 1.4 GHz. As suggested by simulations, the transverse impedance spectrum did not give very clear information on the transverse SPS impedance.

CONCLUSION AND FUTURE WORK

Simulations and measurements were performed to obtain more information on the vertical SPS impedance. The impedance model of the SPS was refined and accounts for 60% of the vertical tune shift slope with intensity. The simulated instability threshold is very close to the measurement, but direct space charge is not yet included in the simulations.

Although the simulated frequency spectrum of a long debunching bunch interacting with a Q=1 broadband impedance gives direct information on the impedance spectrum, the simulated interaction with the SPS kickers resistive wall impedance does not. Combinations of low and high Q resonators will be simulated with various chromaticity settings to see whether different frequency ranges of the SPS impedance spectrum can be separately scanned.

Even though the bunch was vertically unstable in the SPS measurements with long bunches, no clear activity could be observed before the sum signal becomes distorted. It would then be interesting to use the feedback system to try and prevent these distorsions, as well as change chromaticity.

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