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CHARACTERISATION OF BUNCH-BY-BUNCH TUNE SHIFT EFFECTS IN THE CERN SPS

I. Mases Solé*, H. Bartosik, V. Kain, K. Paraschou, M. Schenk, C. Zannini,
CERN, Geneva, Switzerland.

Abstract

After the implementation of major upgrades as part of the LHC Injector Upgrade Project (LIU), the Super Proton Synchrotron (SPS) delivers high intensity bunch trains with 25 ns bunch spacing to the Large Hadron Collider (LHC) at CERN. These beams are exposed to several collective effects in the SPS, such as beam coupling impedance, space charge and electron cloud, leading to relatively large bunch-by-bunch coherent and incoherent tune shifts. Tune correction to the nominal values at injection is crucial to ensure beam stability and good beam transmission. During the beam commissioning of the SPS, measurements of the bunch-by-bunch coherent tune shifts have been conducted under different beam conditions, together with appropriate corrections of the average tunes at each injection. In this paper, we describe the methodology that has been developed to acquire bunch-by-bunch position data and to perform online computations of the coherent tune spectra of each bunch using refined Fourier transform analysis. The experimental data are compared to multiparticle tracking simulations using the SPS impedance model, in view of developing an accurate model for tune correction in the SPS.

INTRODUCTION

In preparation of the high luminosity upgrade of the LHC (HL-LHC), the LHC injectors including the SPS have been upgraded in the framework of the LIU project [1] to enable the production of high intensity and high brightness beams. Due to the high intensity of the bunches, there is a strong bunch-by-bunch coherent and incoherent tune shift in the SPS caused by the impedance. Furthermore, at injection energy the proton beam is sensitive to instabilities induced by the resistive wall impedance. Thus it is necessary to measure the horizontal and vertical bunch-by-bunch tunes and correct the average coherent tunes such that they are close to the central tunes programmed for the bunch-by-bunch transverse damper in order to stabilize the beam. The nominal values of the horizontal and vertical tunes (in the SPS Q20 optics [2]) are $Q_x = 20.13$ and $Q_y = 20.18$.

The bunch-by-bunch transverse tune shift depends strongly on the beam configuration. The most important parameters are the intensity per bunch, and the total intensity of the beam through the number of bunches and the number of batches (i.e. bunch trains from the injector), as illustrated schematically in Fig. 1. In particular, the broadband impedance sources in the SPS (mostly kicker magnets) result in a relatively large tune shift already for single bunches in the machine [3], denoted in the graph as ΔQ_{SB}.

* ingrid.mases.sole@cern.ch

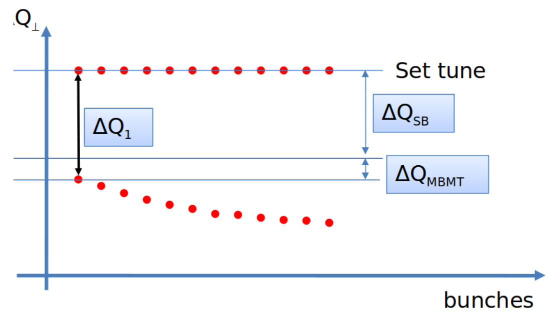

Figure 1: Schematic view of transverse tune shift along the bunch train (explanation in the text).

Due to the resistive wall impedance and other narrow-band impedances in the machine, the wakefield builds up along the train, resulting in a growing tune shift for the trailing bunches. Moreover, if the wakefield does not fully decay within one turn of the machine, an additional tune shift from these long range wakefields is experienced even by the first bunch of the train denoted as ΔQ_{MBMT} in Fig. 1.

The aim of the bunch-by-bunch tunes study is to be able to predict the transverse tune shifts as a function of the beam characteristics. For this purpose, tune shift measurements and adjustments have been carried out in the SPS at different intensities. The methodology followed to carry out the measurements is detailed in the following sections. In addition to the measurements, impedance induced tune shifts as function of intensity have been determined with PyHEADTAIL [4] simulations using the SPS impedance model. Finally, the tune shifts from measurements and simulations are compared at different intensity values.

TUNE SHIFT MEASUREMENTS

The beam position is recorded for several turns after injection into the SPS using the LHC prototype Beam Position Monitors (BPMs) installed in the SPS, as those are the only ones capable of acquiring bunch-by-bunch data. Residual injection oscillations are generally not providing enough signal to noise ratio in the recorded turn-by-turn position data. For this reason, a controlled excitation is applied with a kicker magnet at injection so that the beam oscillations are enhanced. A beam in standard configuration (four trains of 72 bunches each) was used in the measurements. The trains are injected consecutively and, at injection of each train, a kick to all bunches in the beam is applied in order to induce transverse oscillations. This allows measuring the bunch-by-bunch tunes of every train circulating in the machine through a refined Fourier analysis, as described later

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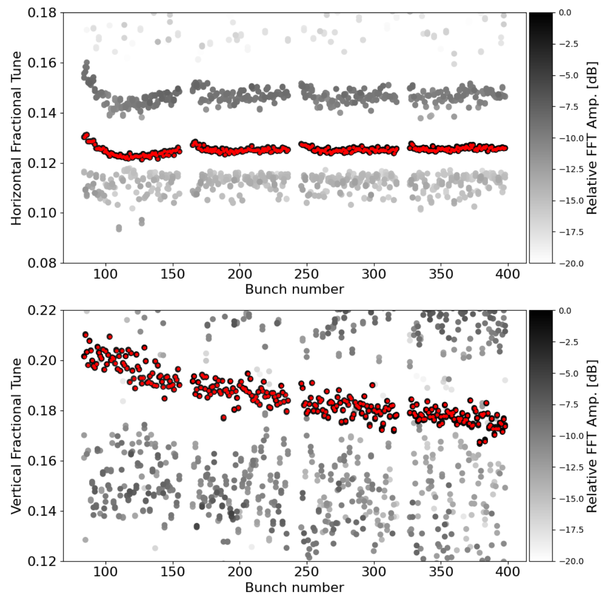

Figure 2: Horizontal (top) and vertical (bottom) bunch-by-bunch tunes measured through LHCBPMs in the SPS for an intensity of 0.8×10^{11} p/b.

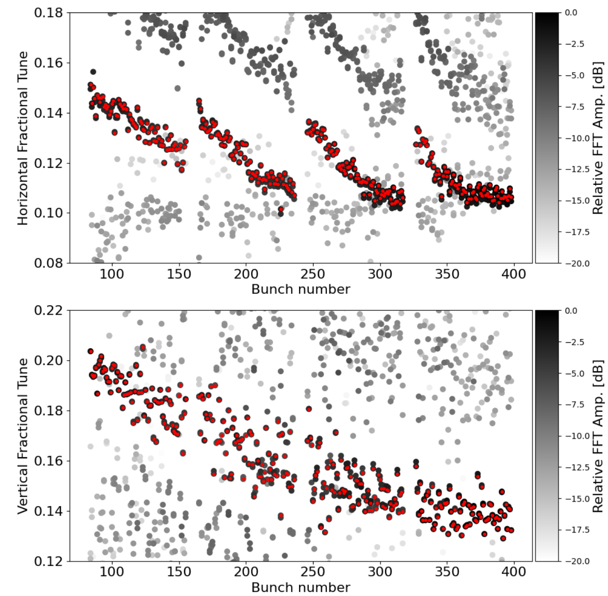

Figure 3: Horizontal (top) and vertical (bottom) bunch-by-bunch tunes measured through LHCBPMs in the SPS for an intensity of 2.0×10^{11} p/b.

on. Horizontal and vertical planes are kicked independently to reduce effects of coupling between planes.

An additional factor to consider while performing measurements is the presence or absence of the bunch-by-bunch transverse damper after injection of bunch trains. The feedback phase of the damper has been adjusted before the measurements with the purpose of obtaining a purely resistive damper [5]. If the feedback phase is not adjusted, the damper may also have a reactive component which means that the tunes measured with and without damper would not have the same value. In the case where the damper is acting on the beam immediately after injection, the beam oscillation amplitudes are significantly reduced, which makes the tune analysis less accurate. Thus, during the tune measurements presented here, the transverse damper is set not to act on the beam for the first 2 ms after the injections with the aim to have clear oscillations. After these 2 ms, the damper is switched on again to suppress transverse instabilities.

The frequency analysis of the collected data is carried out with Harpy [6], a Python code for harmonic analysis based on refined Fourier analysis developed at CERN. Figure 2 shows the harmonic analysis performed on the measured turn-by-turn position data using the first 16 turns. The number of modes taken into account in the calculations is a parameter that can be changed. In this case, 10 modes have been used. All modes are displayed and the one of maximum amplitude (which is the fundamental tune) is shown in red, for each bunch. Moreover, lower amplitude modes are also shown in gray-scale indicating their relative amplitude. Analyzing these modes is useful to identify coupling between planes.

The tune per batch is obtained by computing the median of the bunch-by-bunch tunes over the corresponding batch. At low intensities (as in Fig. 2) it is easier to compute the tunes. In the horizontal plane one can observe the expected flat behavior of the tunes, and in the vertical plane the tune shift accumulating along the train [7, 8]. For higher intensities, measuring the bunch-by-bunch tunes becomes more challenging because of the high chromaticity at which the machine has to operate in order to avoid instabilities. Figure 3 shows the bunch-by-bunch tunes measured at high intensity (2.0×10^{11} p/b). At high intensity, a strong excitation had to be applied to the beam (tune kickers at 3 kV).

Comparing Fig. 2 and Fig. 3 one can observe that the relative tune shift between the first and fourth train in the vertical plane is larger for higher intensity, as expected. On the other hand, in the horizontal plane, at higher intensities (Fig. 3) the bunch-by-bunch tunes do not exhibit flat shape observed at lower intensities (Fig. 2).

SIMULATIONS WITH PYHEADTAIL

Impedance induced tune shifts have been simulated with the PyHEADTAIL macroparticle tracking code using the SPS impedance model that takes into account the wall and kickers contributions, with multi-turn wake fields [8]. The simulations and tune analysis have been carried out under the same conditions as the measurements described above. Nonlinear chromaticity up to third order and nonlinear synchrotron motion are considered in the simulations.

In Fig. 4 and Fig. 5 the bunch-by-bunch tunes at low and high intensity, respectively, are shown. Here the bunch-by-bunch tunes are shown in blue. Simulations studies have shown that the rise time of the vertical coupled bunch instability decreases for higher vertical tunes. Therefore, the vertical set tune has been increased to 20.32 in the simu-

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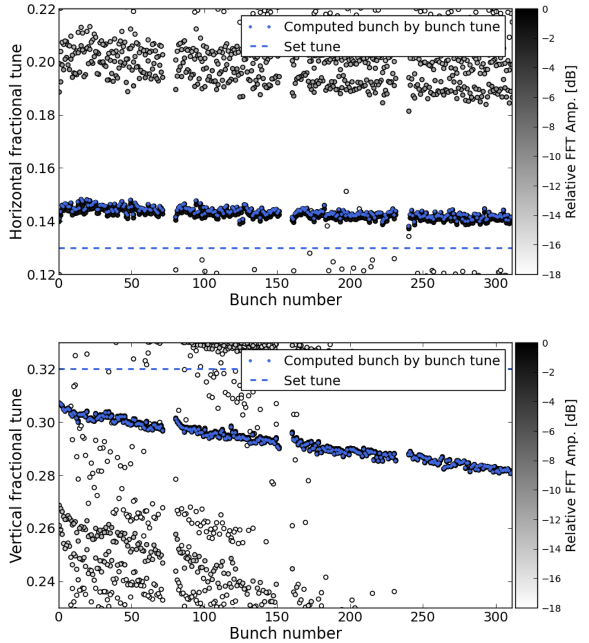

Figure 4: Bunch-by-bunch tunes obtained with PyHEADTAIL simulations, for low intensity of 0.8×10^{11} p/b.

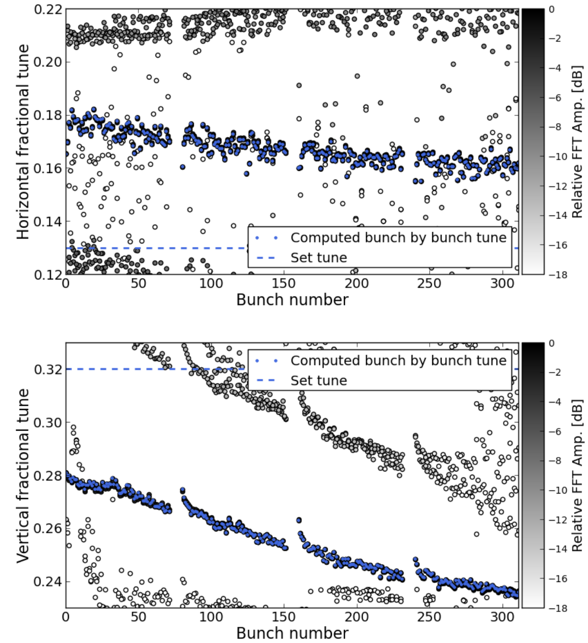

Figure 5: Bunch-by-bunch tunes obtained with PyHEADTAIL simulations, for high intensity of 2.0×10^{11} p/b.

lations, which were performed without damper. As in the measurements, the first 16 turns have been used to compute the tunes. The relative tune shift along the bunch train (which does not depend on the set tune) will be compared with the measurements, instead of the absolute tune values.

At low intensity, simulations reproduce well the bunch-by-bunch behavior seen in the measurements (see Fig. 2 and Fig. 4). On the contrary, at high intensity, the simulations for the horizontal plane do not agree with the shape seen on the measurements (see Fig. 3 and Fig. 5), which might be caused by electron cloud effects [9], which are not taken into account in the simulations.

COMPARISON WITH SIMULATIONS

The tune shift (median tune of first batch minus median tune of last batch) has been computed with both data from measurements and simulations. Figure 6 shows the comparison of the tune shifts for the vertical plane. At low intensities there is relatively good agreement. For intensities above 1.0×10^{11} p/b the discrepancy is more than 20%.

This difference could be explained by the fact that the multi-bunch model used in simulations does not consider impedance sources like BPMs, RF cavities and step transitions, unlike the SPS single-bunch model which has been benchmarked with measurements quite extensively [3]. The resulting underestimation of the single-bunch tune shift of about 30% could play a role when approaching mode coupling due to tune shift with intensity. Furthermore, electron cloud effects, that might become relevant at high intensities, are not considered in simulations. They will be subject of future studies and dedicated measurements.

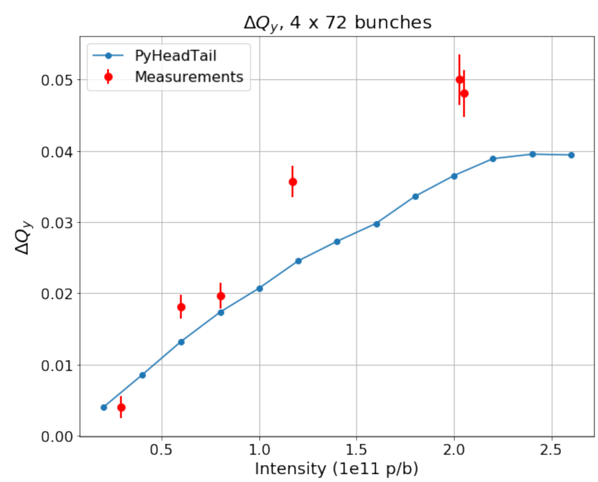

Figure 6: Tune shift of the fourth train with respect to the first train comparing measurements with simulations.

CONCLUSIONS

Tune shift effects are important in the SPS operating at high intensities, and they have an impact on the beam quality. A procedure for measuring the bunch-by-bunch tunes has been established. Tune shift measurements with four trains of 72 bunches have been performed and compared to PyHEADTAIL simulations. In the vertical plane, relatively good agreement between measurements and simulations is found at low bunch intensities. The discrepancy seen at high intensities could be due to the fact that some impedance contributions are currently missing in the model. Discrepancies in the horizontal plane might be caused by electron cloud effects, which will be subject of future studies.

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