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BUNCH-BY-BUNCH TUNE SHIFT STUDIES FOR LHC-TYPE BEAMS IN THE CERN SPS

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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). 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. Measurements of the bunch-by-bunch coherent tune shifts have been performed under different beam conditions. In this paper, we present the measurements of the bunch-by-bunch tune shift as function of bunch intensity for trains of 72 bunches. The experimental data are compared to multi-particle tracking simulations (including other beam variants such as 8b4e beam and hybrid beams) using the SPS impedance model.

INTRODUCTION

In preparation of the high luminosity upgrade of the LHC (HL-LHC) [1], the LHC injectors including the SPS have been upgraded in the context of the LIU project [2] to allow the production of high intensity and high brightness beams. Because of the high intensity of the bunches, there is a pronounced bunch-by-bunch coherent and incoherent tune shift in the SPS caused by the transverse beam coupling impedance. Moreover, at injection energy, the proton beam is sensitive to instabilities induced mainly by the impedance contribution from the resistive wall. In order to stabilize the beam, it is thus necessary to measure the horizontal and vertical bunch-by-bunch tunes at injection and correct the average coherent tunes such that they are close to the central tunes programmed for the bunch-by-bunch transverse damper. The nominal values of the horizontal and vertical tunes, in the SPS Q20 optics [3], 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. The spacing between both individual bunches and trains of bunches is also important, as wakefields decay, which in turn affects the tune shift. Since the majority of SPS vacuum pipes are flat chambers (i. e. no circular symmetry), the horizontal and vertical impedances are not the same, resulting in different bunch-by-bunch tune shifts in the transverse planes. In the vertical plane, the broadband impedance sources in the SPS, i. e. mostly the kicker magnets, result in a relatively large tune shift already for single bunches (denoted in the image as ΔQ_{SB}) in the machine [4]. Due to the resistive wall impedance and other narrow-band impedances in the machine, the wakefield builds up along the train, resulting in an increasing bunch-by-bunch tune shift (denoted as ΔQ_{BbB}) 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 (denoted as ΔQ_{MBMT} in Fig. 1) is experienced even by the first bunches of the train. In the horizontal plane, $\Delta Q_{\mathrm{SB}} \sim 0$ and $\Delta Q_{\mathrm{BbB}} \sim 0$, so the multi-turn tune shift ΔQ_{MBMT} is the responsible for the positive tune shift of all bunches, as seen in Fig. 1 bottom.

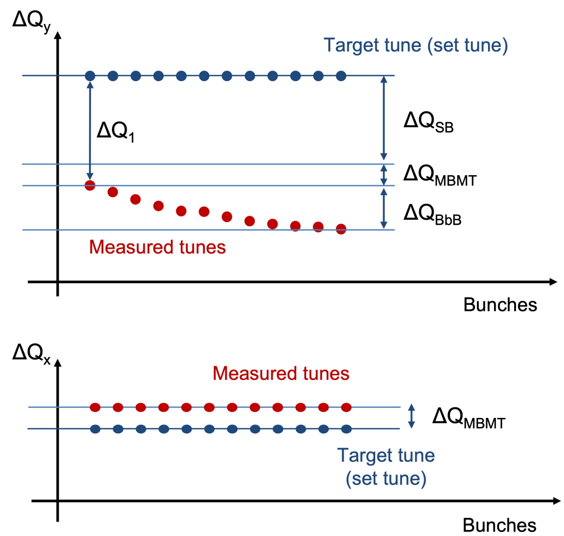

Figure 1: Schematic view of vertical (top) and horizontal (bottom) tune shift along the bunch train (explanation in the text).

Measuring bunch-by-bunch tune shifts at intensities higher than 2.0×10^{11} p/b is not transparent to the machine operation, as it leads to beam degradation, due to the excitation of transverse oscillations required for the measurement. The aim of the bunch-by-bunch tune shift studies is thus to build a model for predicting the transverse tune shifts experienced by each train injected in the SPS as a function of the beam configuration: filling scheme, number of trains, number of bunches and intensity per bunch. The predictive model should allow to compute the tune corrections needed for LHC-type beams without performing measurements dur-

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ing operation. For this purpose, impedance-induced tune shifts have been calculated with PyHEADTAIL [5] simulations. These simulations have been benchmarked with dedicated tune shift measurements carried out at different intensities in the SPS, with the standard beam composed of trains of 72 bunches. The methodology followed to carry out the measurements is detailed in the following sections, as well as the comparison with simulation results. Finally, tune shift simulations for alternative filling schemes are shown.

METHODOLOGY OF MEASUREMENTS

The beam position is recorded for several turns after injection using the LHC prototype Beam Position Monitors (BPMs) installed in the SPS. These particular BPMs are the only ones capable of acquiring bunch-by-bunch data. Residual injection oscillations typically do not provide a sufficient signal-to-noise ratio in the recorded turn-by-turn position data. To address this, a controlled excitation is applied to the beam using a kicker magnet to excite beam oscillations, a few milliseconds after injection. Since the trains of bunches are injected consecutively, a kick is applied to all bunches on the beam upon each new injection. This enables the computation of tunes at each injection using refined Fourier analysis, as described later on. To minimize the effects of transverse coupling, horizontal and vertical planes are excited independently.

Another aspect to consider while performing measurements is the gain of the bunch-by-bunch transverse damper. In the case where the damper is acting on the beam with the operational gain setting immediately after injection, the beam oscillation amplitudes are significantly reduced, which makes the tune analysis less accurate. Thus, during the tune measurements presented in this paper, the transverse damper is set to zero gain for the first 2 ms after the injections with the aim to have clear oscillations. After these 2 ms, the damper gain operational setting is restored to suppress transverse instabilities. Figure 2 shows the horizontal turn-by-turn data measured after injection of the fourth train, in the case of 4×72 bunches.

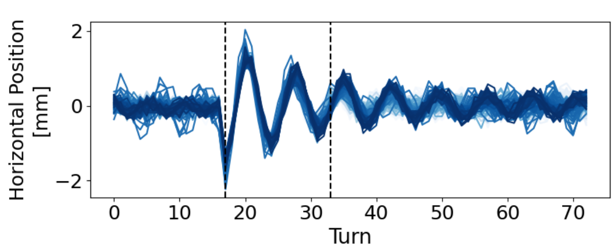

Figure 2: Horizontal positions captured turn-by-turn by the LHC-BPMs in the SPS. Each trace on the graph represents the position of an individual bunch. For this particular measurement, there were 4×72 bunches. The excitation applied to the beam can be observed at turn 17 on the plot.

The frequency analysis of the collected data is conducted using Harpy [6], a Python code for harmonic analysis based on refined Fourier techniques developed at CERN. Harmonic analysis is carried out on the first 16 consecutive turns after the excitation is applied to the beam. This specific number of turns is chosen to ensure optimal quality and integrity of the signal. Extending the dataset beyond this limit generally results in degradation of the signal quality.

MEASUREMENTS

Following the methodology described in the previous section, a series of measurements was conducted, in order to characterize the bunch-by-bunch tune shifts as function of intensity, in both transverse planes. These measurements were done in two different scenarios; with a single train (1×72 bunches) and with multiple trains (4×72 bunches). The measurements performed with multiple trains are explained in detail hereunder. Both cases, 1×72 and 4×72, will be compared to multi-particle tracking simulations in the subsequent section devoted to simulations.

In the 4×72 bunches scenario, an intensity scan was performed, ranging from 0.28×10^{11} to 2.15×10^{11} p/b and starting from the higher value. Prior to initiating the intensity scan, the tunes for each train were preset to specific values: Given that this scenario involves four injections, the tunes were measured and corrected such that the median tune of each newly injected train was obtained as $Q_x/Q_y = 20.13/20.17$. This accurate adjustment at every injection was carried out just once at the beginning of the scan. Later, during the intensity scan, the bunch-by-bunch tunes were measured only when all four trains were circulating in the machine. Therefore, the kick was applied to the beam after the injection of the last train. During the intensity scan, no tune corrections were made, as the focus was on measuring the bunch-by-bunch tunes in both planes as a function of varying intensity. At high 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. A strong excitation (tune kickers at 2.5 kV) had to be applied to the beam to perform the measurements. Figure 3 displays the vertical bunch-by-bunch tunes of the four trains at the various intensities measured, as indicated by the color code.

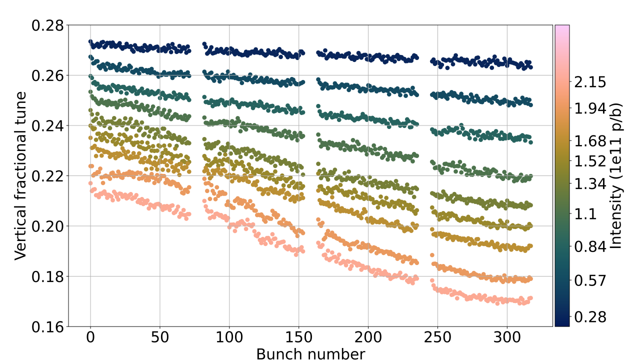

Figure 3: Measured vertical bunch-by-bunch tunes at different intensities, with 4×72 bunches. The color scale indicates the measurement intensities.

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Two effects are observed with increasing intensity: first, the tunes of all bunches shift downwards, and second, the tune shift accumulates along the train [7, 8]. At higher intensities, the bunches at the end of the train exhibit larger tune shifts compared to the leading bunches. Comparing the tunes at high and low intensities reveals that the relative tune shift between the first and fourth train is larger at higher intensities, as expected. Focusing on the average tune of the last batch, the observed tune shift in this intensity range is $\Delta Q_y \approx -0.1$. This observation underlines the importance of correcting the tunes based on intensity to ensure both beam stability and quality, and to minimize losses.

Bunch-by-bunch tune measurements for the horizontal plane are displayed in Fig. 4. It can be observed that the tune shift dependence is quite different compared to the vertical plane: the tune increases with higher intensity due to the negative detuning impedance. Moreover, the tune shift along the train is less pronounced than in the vertical plane.

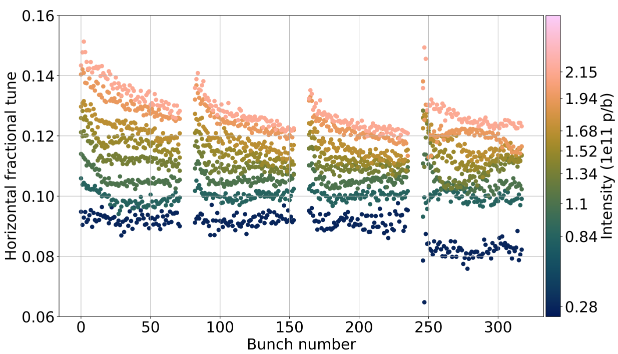

Figure 4: Measured horizontal bunch-by-bunch tunes at different intensities, with 4×72 bunches. The color scale indicates the measurement intensities.

At low intensities, the bunch-by-bunch tunes are almost flat along the trains, as expected from impedance-related effects. In addition, for the lowest intensity (dark blue color), smaller tunes are measured on the last train as compared to the leading ones. This behavior might be attributed to the mode -1 that becomes dominant due to decoherence from chromaticity or non-linearities. In fact, when performing the frequency analysis, it is observed that the main tune may experience jumps of Q_s depending on which mode exhibits the highest amplitude. Another important observation is that at high intensities, the tune along the trains deviates from the flat shape observed at lower intensities.

In addition to the multi-train scenario, measurements with a single train were also conducted. An intensity scan was performed, ranging from 0.88×10^{11} to 2.32×10^{11} p/b. The tunes were initially adjusted at the lowest intensity and remained unchanged throughout the scan. The results of these measurements will be compared to simulations in the subsequent section.

COMPARISON WITH SIMULATIONS

Impedance induced tune shifts have been simulated with the PyHEADTAIL [5] macroparticle tracking code using the SPS impedance model that takes into account the wall, kickers and transitions contributions, with multi-turn wakefields [8]. The simulations and tune analysis have been carried out under the same conditions as the measurements described in the previous section. Simulations are performed without transverse damper and the excitation (kick) is applied to the beam at the same time as done in the measurements, in order to take into account the build up of wakefields along multiple turns. Nonlinear chromaticity up to third order [9] and nonlinear synchrotron motion are considered in the simulations. As in the measurements, the first 16 turns after the excitation have been used to compute the tunes.

Bunch-by-bunch tunes have been simulated for both the 1×72 and the 4×72 bunch case, using the same intensities employed in their respective measurements. For the 1×72 bunch scenario, the comparison between the measurements and simulations for both planes is shown in Fig. 5.

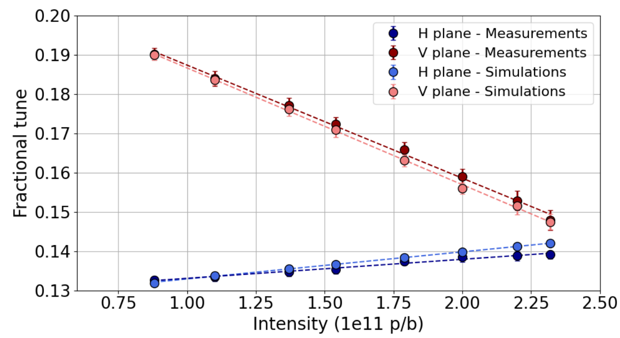

Figure 5: Median tune of the train of 72 bunches, as determined by measurements and PyHEADTAIL simulations for both horizontal and vertical planes. The dashed lines represent the linear fit for each set of data.

The median bunch-by-bunch tune of the batch is plotted here, in order to remove outliers in the tune analysis (e. g. caused by noisy BPM data). In both planes, the measurements and simulations are in very good agreement, with the median tune varying linearly with intensity. As previously noted, the vertical tune shift is negative as intensity increases, whereas the horizontal tune shift is positive; however, the absolute value of the slope in the horizontal plane is six times smaller than that in the vertical plane, as can be observed in Fig. 5.

Simulations involving multiple trains have been conducted for comparison with the measurements displayed in Figs. 3 and 4. Figure 6 shows the vertical and horizontal median tunes of each train at the different intensities, for both measurement and simulation data. The agreement is very good; the bunch-by-bunch tunes computed from simulations exhibit the same behavior with respect to intensity as observed in the measurements.

In the horizontal plane, the simulations accurately replicate the bunch-by-bunch behavior observed in low-intensity measurements (apart from the one measurement with 0.28×10^{11} p/b intensity discussed in the previous section). At high intensities, however, the simulations slightly diverge from

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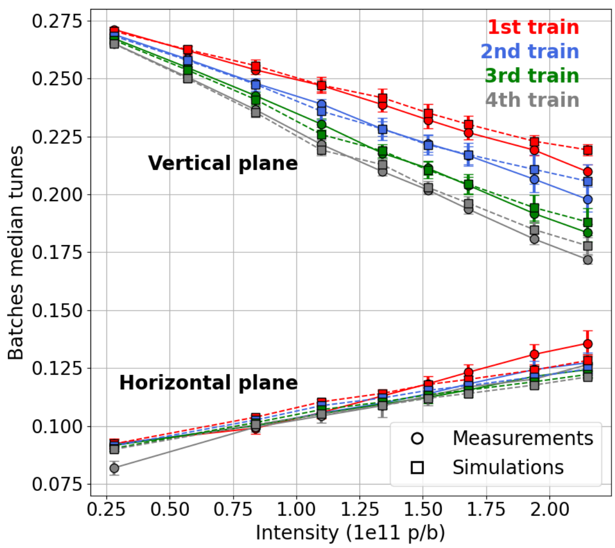

Figure 6: Median tune for each of the four trains of 72 bunches, as determined by both measurements and PyHEADTAIL simulations in both planes. Circles represent measurements, while squares denote simulations. Different colors indicate the respective trains.

the values measured and shown in Fig. 4. Specifically, the simulations do not exhibit the pronounced tune shift within trains that is observed in high-intensity measurements [10] (cf. Fig. 4). This difference might be due to electron cloud effects [11] not considered in the simulations, or due to coupling between the horizontal and vertical planes, which is also not accounted for in the simulations. To understand these discrepancies will be the subject of future studies.

In addition to the intensity scan, an interesting behavior was observed in the horizontal plane during measurements. Specifically, all bunches undergo a positive tune shift of $\Delta Q_x \sim 0.01$ each time a new train is injected. This phenomenon is also evident in simulations, as illustrated by the results shown in Fig. 7, which detail how the tune of each train changes with each new injection.

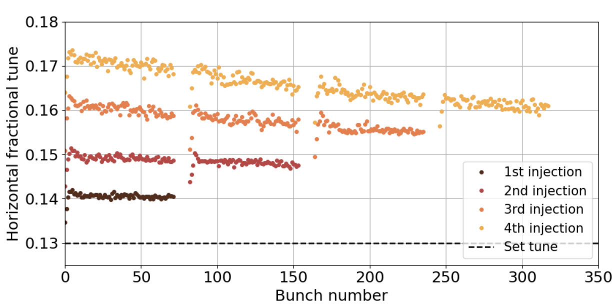

Figure 7: Simulations of the evolution of the bunch-by-bunch horizontal tunes as trains are injected in the SPS.

The dashed line represents the set tune ($Q_x = 20.13$), which remained constant throughout the simulation. Notably, the median tune shifts from $Q_x = 20.14$ when a single train is circulating, to $Q_x \geq 20.16$ when all four trains are in the machine. The mechanism responsible for this tune shift with total intensity in the machine is currently under study.

COMPARING TUNE SHIFTS FOR DIFFERENT FILLING SCHEMES

Over the past year, various filling schemes for LHC-type beams have been tested in the SPS, to mitigate electron cloud effects in the LHC. One such scheme is the '8b4e' filling scheme, which consists of trains composed of 56 bunches arranged in a specific pattern: eight bunches followed by four empty bunch slots (as seen in red in Fig. 8). Another is the 'hybrid' scheme, which features an initial 8b4e train followed by five trains, each consisting of 36 bunches (as seen in green in Fig. 8). Bunch-by-bunch tunes have been simulated with PyHEADTAIL for each of these scenarios in order to compare them.

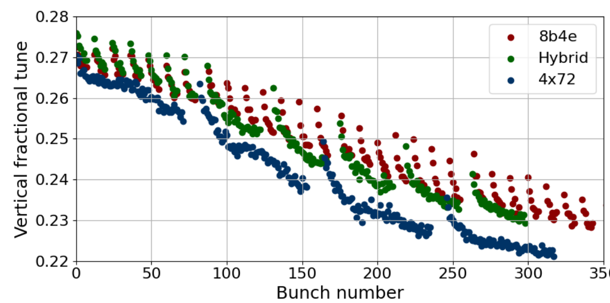

Figure 8: Comparison of bunch-by-bunch tunes for three different filling schemes at 2.0×10^{11} p/b: 4×72 bunches (blue), four trains of 8b4e (red), and the hybrid beam (green).

In the 8b4e configuration, the bunches experience a reduced tune shift along the train, because of the decay of wakefields in the empty gaps. Consequently, this results in less accumulated tune shift compared to the standard scheme involving trains of 72 bunches. Similarly, in the hybrid configuration, the shorter trains of 36 bunches lead to a smaller accumulation of tune shift as compared to the standard scheme. These simulations will also be incorporated into the predictive model to facilitate tune adjustments across various filling schemes.

CONCLUSIONS

Tune shift effects are important when the SPS operates at high intensities, as they significantly impact beam quality. Tune shift measurements with both 1×72 and 4×72 bunches trains have been conducted and compared with simulations. Good agreement between the measurements and simulations with the SPS impedance model has been observed in both transverse planes. Small discrepancies in the horizontal plane observed at high intensities are under study. These results are being used to develop a predictive model for tune shifts in the SPS, specifically for LHC-type beams, aiming at tune corrections without excitation of transverse oscillations to avoid compromising beam quality.

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