FAST BUNCH BY BUNCH TUNE MEASUREMENTS AT THE CERN PS

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Abstract

The CERN Proton Synchrotron (PS) is a crucial component of the Large Hadron Collider (LHC) injector complex. The role of the PS is to provide beams of high brightness and with the required time structure. In this paper, the results of bunch-by-bunch (BxB) tune measurements by using turn-by-turn transverse beam position monitors (BPMs), are presented. The data from different BPMs are combined together to allow fast and accurate tune measurements for each bunch. The obtained results are compared with the present PS tune-meter system and the specific advantages and limits of this technique are commented and exemplified.

INTRODUCTION

The PS [1] operates at a kinetic energy of 1.4 GeV at injection, and delivers beams to the downstream experiments in an energy range between 14-26 GeV. Several Machine Development (MDs) measurements are performed, in order to investigate the suggested improvements for the planned LHC Injectors Upgrade [2]. As a part of these MDs, the betatron tunes are measured at the injection of the PS, by using turn by turn (TxT) transverse position data from the 43 BPMs of the PS [3]. For the data discussed in the following, 625 turns for each of the 4 bunches injected from the Proton Synchrotron Booster (PSB) are recorded, using the same cycle, at 3 different positions in the sequence of cycles [4] of the PS. The betatron tunes are estimated by mixing all the BPM data together and using the Numerical Analysis of Fundamental Frequencies (NAFF) [5] algorithm in order to obtain the highest resolution for the smallest possible number of turns. In this analysis, a comparison is undertaken between the measured tunes and the measurements of the operational tune measurement system (BBQ) [6], for the different bunches and cycle positions. In addition, the impact of the injection bump on the betatron tunes is quantified. Finally, the correlation of the horizontal tunes with the mean radial position (MRP) of the bunches along the PS sequence of cycles is shown and some conclusions are given.

BUNCH BY BUNCH TUNE MEASUREMENTS AT INJECTION

The injection oscillations in both planes are produced from injection missteering. Bunches that are horizontally injected closer to the closed orbit (CO) perform weaker betatron oscillations. Since the BPMs measure the transverse excursions from the CO, it is expected that the TxT signal from these particular bunches will have a lower signal to noise ratio (SNR). The four bunches injected from the PSB to the PS, exhibit different injection oscillations due to

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the differences in the PSB extraction trajectories and to the marginal difference in the energies of the four bunches [7, 8]. These differences are usually corrected during nominal operation, e.g. when pulsing bunches to the LHC for collision. However, during this MD these corrections are not applied , in order to benchmark a novel tune measurement technique. As a result, the recorded TxT signal from the four different bunches varies in amplitude, and this is testified in Fig.1, where the first 100 turns recorded from the position monitor "BPM 43", which is located in the region of the injection bump, are shown. Bunch number 2 is performing strong horizontal oscillations (12 mm peak-to-peak value) whereas bunch number 3 horizontally and bunch number 1 vertically, are almost at the noise level of the instrument (below 1 mm peak-to-peak). Note that SNR is also affected by intensity, but all four bunches are injected with the same intensity from the PSB.
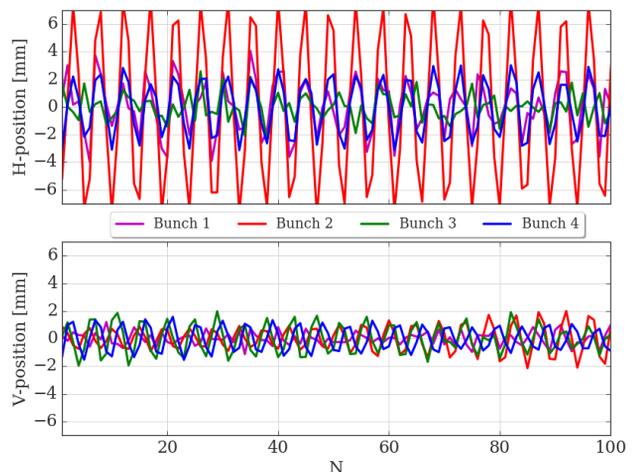

Figure 1: The TxT horizontal (top figure) and vertical (bottom figure) injection oscillations, after removing the closed orbit, for the first 100 turns, as seen at "BPM 43". Bunch 1 is shown in magenta, bunch 2 in red, bunch 3 in green and bunch 4 in blue.

In order to estimate the number of turns that would give an acceptable resolution, the betatron tunes are measured by mixing all the BPM data together [9, 10] for the first 100 turns. The measurements of the horizontal tunes for bunch 3 and of the vertical tunes for bunch 4, can provide a minimum tune resolution, since both exhibit small oscillations compared to the other two bunches, as Fig.1 shows. The results can be seen in Fig.2, where for bunch 4, the convergence is already at around 10^{-4} from the first 20 turns. The horizontal tune from bunch 3 cannot be estimated at the same interval. After 20 turns, the measurements begin to converge slowly to a value at 40 turns. Thereafter, the horizontal tune slowly drifts upwards signifying the presence of a transient effect.

In order to accommodate for the slow convergence of bunch 3, a window of 40 turns is chosen for the rest of the analysis, which provides a convergence at the level of 10^{-4}. It is expected thus, that the minimum tune resolution will be at that level, for all bunches.
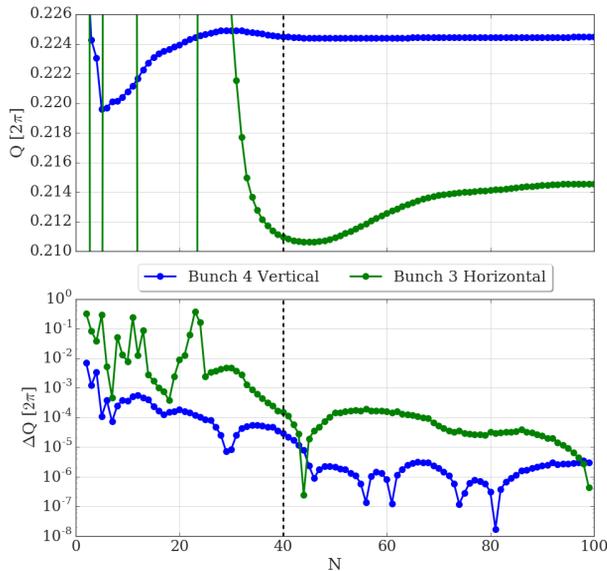

Figure 2: Top figure: The horizontal tunes for bunch 3 (in green) and the vertical tunes for bunch 4 (in blue), by mixing all the TxT together, with an increasing window from turn 1 to turn 100. Bottom figure: The TxT absolute convergence of the above tunes i.e. the absolute difference of consecutive measurements.

Comparison with the BBQ System

The BBQ system is used for measuring the tunes during operation, by exciting the beam and performing standard FFT analysis, averaged over all bunches. For this particular MD, the BBQ uses 2048 turns for the estimation of the tunes. The BBQ measurements, as well as the TxT data, are gathered at three positions in the sequence of the PS cycles which are referred as "Slot 13", "Slot 32" and "Slot 35". While the BBQ system cannot provide BxB information, this information can be recovered from the BxB TxT data. The results can be inspected in Fig. 3, where the average horizontal and vertical tunes for bunch 4 are shown at the different cycle positions, for the first 40 turns along the tune estimations from the BBQ system. The other bunches are omitted from the figure since they exhibit the same behaviour, except bunch number 3 whose reproducibility is poor.

The error bars are the statistical errors of one standard deviation, with respect to the 60 consecutive measurements. For bunch 4 horizontally, the reproducibility is at the order of 10^{-4}, which is remarkably close at the statistical error of the BBQ measurements. In the vertical plane, the reproducibility is slightly worst for both measurements, due to the fact that the horizontal oscillations are larger than the vertical, as it has been already shown in Fig. 1.

There is a clear discrepancy in the horizontal plane, at the order of $5 \cdot 10^{-3}$, between the results of the BBQ and the TxT frequency analysis, while this offset is absent in the vertical plane where the bunch 4 measurements are within the statistical errors of the BBQ measurements. In addition, both BBQ and bunch 4 measurements, overestimate the tunes measured at "Slot 13" by a factor of 10^{-3}, with respect to the measurements at the other two cycle positions. This offset is larger in the vertical plane, where the chromaticity is larger by about 20%. A small offset between "Slot 32" and "Slot 35" is also present and more evident in the horizontal plane. This behaviour of the tune measurements, can be attributed to hysteresis effects from the systematic error of the on-line operational magnetic measurement (B-train) [11], which controls the dipolar component of the 100 combined function magnets. Due to this, beams of the same cycle, but at different positions in the cycle sequence, appear to have a systematic offset in the mean radial Position (MRP), i.e. the average horizontal orbit.
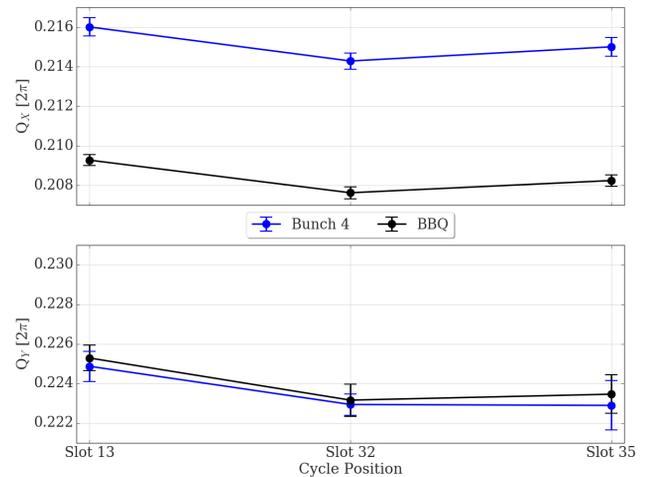

Figure 3: The horizontal (top figure) and vertical (bottom figure) tunes of bunch 4 (in blue) measured during the first 40 turns, with respect to the 3 different positions in the cycle. The results of the BBQ measurements (in black) are also shown.

THE IMPACT OF THE INJECTION BUMP ON THE TUNES

In order to investigate the observed discrepancy, the tunes are measured in consecutive windows of 40 turns and the results are shown in Fig.4. A striking observation is that the tunes of both planes exhibit a strong dependence with the number of turns, reaching a maximum tune-shift of around $1.4 \cdot 10^{-2}$ with respect to the first measurement at 40 turns. The TxT modulation of the betatron tunes can be correlated with the evolution of the horizontal orbit of the bunches, during the time interval that the injection bump is open. The TxT horizontal orbit of bunch 1, measured at the monitor "BPM 43" which is located in the region of the injection

bump , can be visualized in Fig.5. The injection bump produces a large horizontal orbit shift at the order of 25 mm on the first turn and gradually decreases with a steady slope until 500 turns. This orbit shift can be appreciated by comparing with the orbit at "BPM 45", which is located downstream of "BPM 43. In Fig.4, the tune modulation stops after 520 turns, exactly when the orbit at "BPM 43" has been restored. The measured tune offset appears to be related to the TxT variation of the magnetic field of the injection bumpers, i.e. the $\dot{B}$. This leads to the hypothesis that the effect could be driven by the vacuum chamber eddy currents. In addition,the horizontal tunes of all bunches begin with a certain spread at 40 turns reaching a minimum spread at around 400 turns and they end up at opposite positions at the end. The same pattern can be observed in the vertical plane, albeit with lower resolution due to the small vertical oscillations and the residual dispersion. This effect is a signature of synchrotron oscillations which are coupled to the betatron tunes through chromaticity. In fact, this observation allows to investigate the injection error in the longitudinal plane.
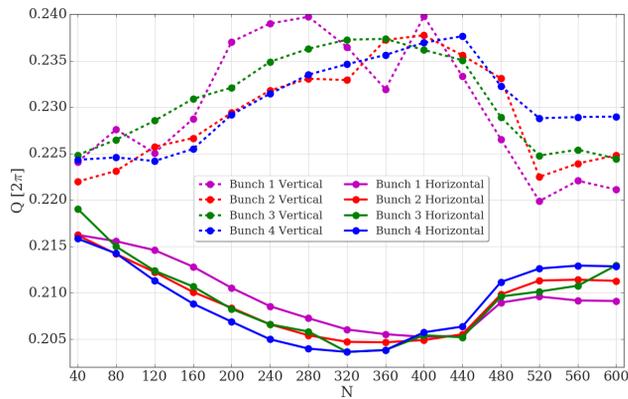

Figure 4: Horizontal and vertical tune measurements for all 4 bunches, by sliding a window of 40 turns along the TxT signal. The horizontal tunes are indicated by thick lines and the vertical by dashed lines.
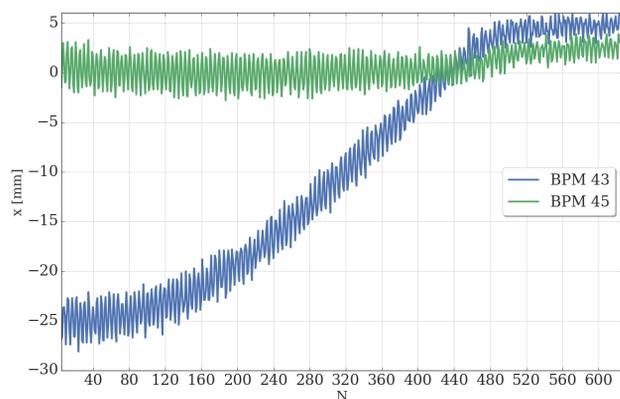

Figure 5: The TxT horizontal orbit of Bunch 1 at the BPM located at the injection bump (in blue) and at the downstream BPM (in green).

Correlation of the Horizontal Tune and the MRP

The MRP is measured for each of the 60 data sets, by averaging the horizontal orbit for the first 40 turns between all BPMs and for all the bunches, except for bunch 3. A periodic oscillation of the MRP along the PS cycle is observed, in accordance to the systematic error of the B-Train. Since, any modulation of the dipolar component of the PS magnets, induces a change in the quadrupolar component, it is expected that the horizontal tunes will be modulated accordingly. This effect can be visualized in Fig.6, where the horizontal tunes for the first 40 turns are shown with respect to the MRP measurements, for all 60 datasets. There is a clear anti-correlation of the two quantities which is due to the fact that the PS at injection operates with negative chromaticity. In fact, the horizontal chromaticity during the MD can be estimated from the slope of Fig.6, if it is assumed that there is no change in the dipolar magnetic field for 40 turns. The total tune-shift is at the order of 10^{-3}. The different areas for each bunch signify once again the energy jitter between bunches.
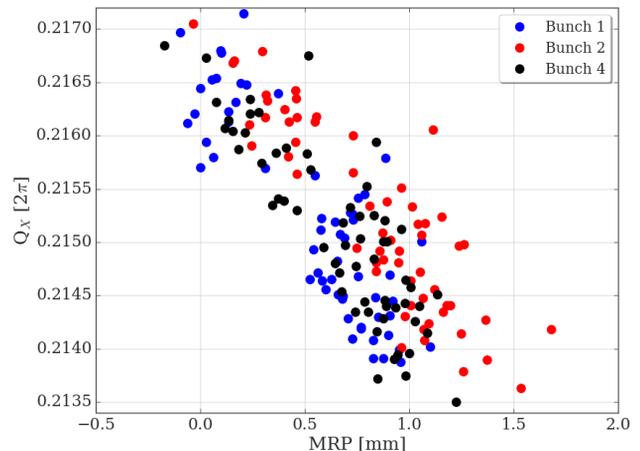

Figure 6: Correlation of the horizontal tune with the MRP for all the positions in the cycle, for bunch 1 in blue, bunch 2 in red and bunch 4 in black.

CONCLUSIONS

The betatron tunes of the PS ring at injection are measured by mixing the BPM data together. This powerful method allows to accurately measure the tunes at injection for all bunches and resolve fast tune-transients without perturbing the beam. The measurements reveal a maximum tune shift of the order of 10^{-2} during injection and confirm hysteresis effects along the PS cycle sequence and the presence of an energy jitter for the bunches at injection. Further studies are needed for a better understanding of these phenomena.

ACKNOWLEDGEMENTS

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