6th International Particle Accelerator Conference IPAC2015, Richmond, VA, USA JACoW Publishing
ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPTY043

ANALYSIS OF INTENSITY-DEPENDENT EFFECTS ON LHC TRANSVERSE TUNES AT INJECTION ENERGY

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Abstract

The LHC Run I has provided a huge amount of data that can be used to deepen the understanding of the beam behaviour. In this paper the focus is on the analysis of transverse tunes at injection energy to detect signs of intensity-dependent effects. BPM data, recording the injection oscillations of the operational beams during the ring-filling phase, have been analysed in detail to enable extracting useful information about the tune shift vs. injected beam intensity. The data processing and the results are discussed in detail, including also possible implications for future operation.

INTRODUCTION

During the first years of LHC operation [1] a gold mine of observations and beam measurements has been collected. Among the several aspects of beam dynamics that can be probed thanks to these data, the evolution of the transverse tunes along the cycle are of particular interest [2]. The tune variation is mainly governed by the magnetic fields and any time-variation of the quadrupolar fields is impacting on the tune stability, which, in turns, might affect the accelerator's performance. Moreover, comparison of the measured tune evolution against the known features of the magnetic model can lead to improvements to the predictivity of the model in view of, e.g., defining a feedforward correction to ease the feedback system.

The data taken during normal operation have already highlighted a good agreement with the prediction of the magnetic model. However, a clear sign of intensity-dependent effects has been observed [2]. Such an effect is visible in the tune evolution during the filling process at injection in the LHC. The standard data analysis applied in Ref. [2] could not provide any quantitative estimate of the tune shift as a function of beam intensity. This effect had been quantified in Ref. [3] based on a number of assumptions for the estimate of the so-called Laslett coefficients [4, 5] (see also Refs. [6–8] for additional detail on this topic). Also in the case of the tune variation with intensity, a feedforward approach could be taken to devise a compensation strategy. Clearly, one should also asses whether this effect could impact the beam dynamics and the beam quality, and a quantitative evaluation of the phenomenon is the first step in this process.

In this paper an improved analysis of the data collected during the operational LHC fills, mainly during the 2012 physics run, is presented. It allows deriving the measured tune shift as a function of intensity. The delicate and interesting topic of comparing the theoretical estimate with observations is left aside for the time being.

MEASUREMENT METHODS

The LHC Base-Band-Tune, BBQ [9], is the most sensitive instrument for tune measurement and provides reliable measurements for single bunches or when the LHC transverse damper (ADT) is not active. For the case of circulating bunch trains, the signal level drops below the noise lines corresponding to 50 Hz harmonics and the noise introduced by the ADT, thus preventing any reliable measurement (see Fig. 1). BBQ data are logged continuously in the form of turn-by-turn data, post-processed spectra, and estimated tune values. Continuous turn-by-turn data are only available for limited periods of time.

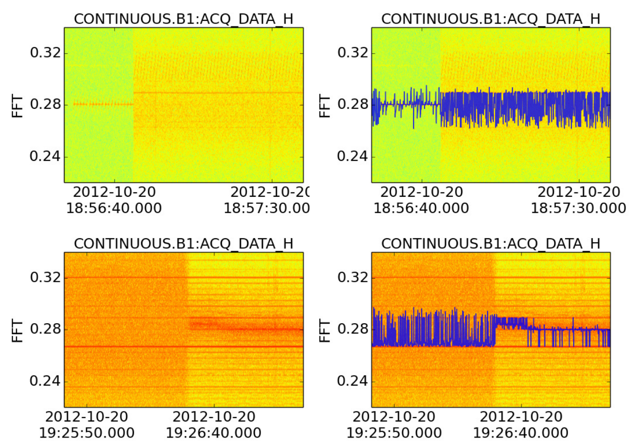

Figure 1: Horizontal BBQ spectra as a function of time (right) with superimposed estimated tune values (blue lines) during the injection process. In the top-left plot the horizontal (0.28) and vertical tunes (0.31) can be recognized when only a pilot bunch is present. However, as soon as other bunches are injected and the ADT activated the noise exceeds the signal level and the estimated tunes are extremely noisy. The bottom figures show the transition when the ADT is switched off, revealing again the tune signature. In fact, the estimated tune values become more reliable, although still occasionally lock on noise lines.

The LHC ADT [10] uses special BPMs and electronics to provide sensitive bunch-by-bunch, turn-by-turn beam position measurements. The 4 BPMs are installed in the insertion region (IR) 4 in the quadrupoles Q7 and Q9 for both beams and transverse planes. Raw data are not logged systematically, as only the 2000 turns of the first injected bunch are available in the logging database. An example of the information available from these BPMs is shown in Fig. 2, where typical injection oscillation signals are shown. A fit with an exponentially decaying sinusoid shows an excellent

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agreement, in particular with the dispersion-free BPM (Q7) data. ADT BPM data are used as primary source for the rest of the study.

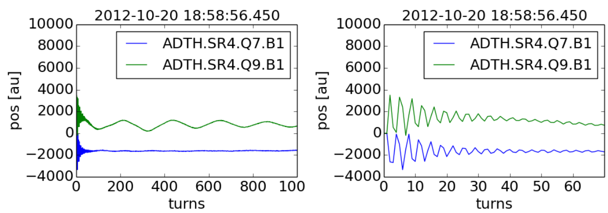

Figure 2: Horizontal position of the first bunch of the last injected batch as measured by the ADT BPMs in Q7 and Q9 of IR4 for the whole data set sampled (left) and during the injection oscillations (right). The effect of non-zero dispersion and synchrotron oscillations can be detected in the Q9 data. Damping time constants are in the order of 16 turns.

In addition, LHC BPMs can also provide bunch-by-bunch and turn-by-turn beam positions, but with a limited sensitivity (see Fig. 3). The data for selected BPMs and bunches are stored at each injection in the post mortem database. The BPM sensitivity is much lower than that of the ADT BPMs so that the number of turns for which the amplitude of injection oscillations is large enough to generate useful data is rather limited. This, in turn, limits the accuracy of the estimate of the tune value. Nonetheless, an interesting bunch-by-bunch modulation of the damping time has been observed (see Fig. 4, top), revealing that the signal of few bunches, those at the edge of the PS batches, can indeed be used reliably for tune analysis and reconstruction (see Fig. 5). The systematic shift of the average tune of the bunches in the middle of the PS batch is considered an artifact due to the small number of useful oscillations above the noise. An optimal choice of the turns to be taken into account in the harmonic analysis would improve the significance of the average tunes for all bunches.

In conclusion, the analysis made shows that the most reliable source of tune measurement at injection during LHC Run I is the ADT BPMs turn-by-turn data for the first bunch of every injected SPS batch and the LHC BPMs for the first bunch of each PS batch (corresponding to 2, 3, or 4 bunches in the LHC) for each injected SPS batch.

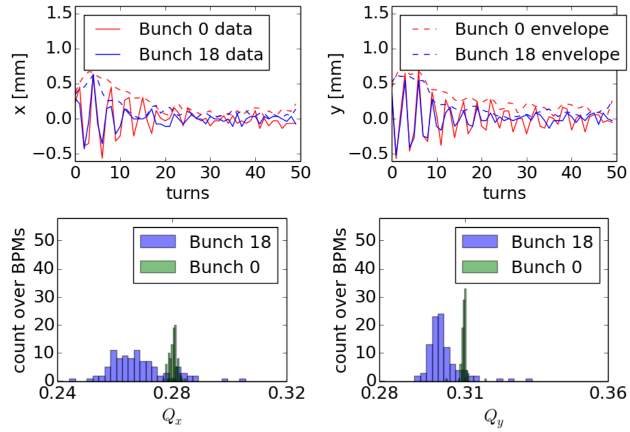

Figure 3: Raw data from one LHC BPM of bunch-by-bunch H/V injection oscillations for 2 bunches (top) and distribution of tune estimates from all BPMs. Bunch 0 is the first of the injected train, while 18 is in the middle of the PS batch. The raw data and the envelope (from a Hilbert transform), show the difference in damping times, which is reflected in the accuracy of the corresponding tune estimates.

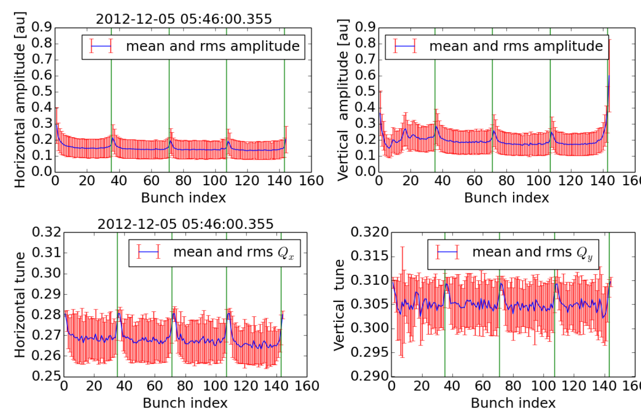

Figure 4: Example of LHC BPM bunch-by-bunch injection oscillation amplitude (top) and related tune estimates (bottom) for one injected SPS batch made of 4 × 36 bunches, with a bunch spacing of 50 ns (PS batches, spaced by 450 μs, are made of 36 bunches). The horizontal axis shows the bunch index, where 1 stands for the first injected bunch and green lines show the location of the PS batch gap edge. The blue lines and red bars represent the average and rms over the available BPMs, respectively.

RESULTS

The validation of the different instruments to measure the tune gave confidence in the use of the turn-by-turn data from the ADT to calculate the intensity-dependence of the tune. The first step in this process is the reconstruction of the bare tunes from the measured values. In fact, the measured tunes are the result of the magnetic state of the ring plus a number of other effects, which are specifically, the b_2 decay and the effect of the tune trim quadrupoles, referred to as the MQTs. The first phenomenon is typical of superconducting magnets and can be modelled by a decaying exponential (see Ref. [2] and references therein), whose parameters are well-known. The exponential variation of the tune starts at the beginning of the injection flattop. The latter effect has to do with the tune feedback, which is aimed at controlling the tune evolution. This is achieved by using the MQTs as tune correctors, which means that their impact on the tune has to be removed from the measured values. This can be simply done by using the linear correction matrix that gives the tune variation induced by the MQTs for a given current variation.

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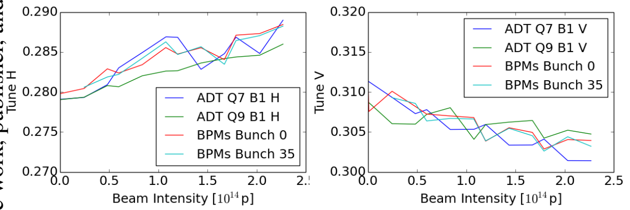

Figure 5: Comparison between tune estimates using data from LHC BPMs and ADT BPMs. The ADT tunes are obtained from the oscillation of the first bunch of the injected batch for single BPMs (Q7 and Q9). The LHC tunes are obtained by averaging over about hundred BPMs the tunes obtained by bunch-by-bunch oscillations for the first bunch of the first (Bunch 0) and second (Bunch 35) PS batch. The tune estimates agrees well and clearly show a consistent trend as a function of intensity. A correction of the effect of the MQ decay and MQT trims to study true intensity dependent effects has not been applied and will be the topic of the next section.

By taking into account of these two phenomena, it is possible to estimate the tune variation occurring at each new injection during the filling process. After the bare tunes have been calculated along the whole filling process, the data are fitted with a straight line. Out of the 950 operational fills of the 2012 run a subset is selected, retaining only those fills for which at least 8 injections, each of 144 bunches spaced by 50 ns, have been successfully completed and the total beam intensity is larger than 5×10^{13} p. The set of fit parameters has been analysed and an additional rejection threshold has been set: all fills for which the fit uncertainty on the slope of the straight line is larger than 3×10^{-17} are discarded. In total less than 15 % of the fills are rejected for this reason. This gives a total of about 350 fills for each of the two beams that have been used for the analysis presented in this article.

The weighted average and standard deviation of the slope of the tune as a function of total beam intensity is then calculated for each of the pick ups used by the ADT and each transverse plane. The errors are only statistical, meaning that any source of systematic uncertainties in the tune decay or tune change of the MQTs are not taken into account in this analysis. The histograms of the tune-intensity dependence are shown in Fig. 6 for Beam 1 and in Fig. 7 for Beam 2. The horizontal tune is increasing with intensity while the vertical tune is decreasing. The results from the BPMs at Q7 and Q9 are consistent with each other and also between the two beams. Moreover, the slopes for the two transverse planes are opposite in sign and of equal magnitude within the statistical uncertainty.

CONCLUSIONS

Intensity-dependent tune shifts have been clearly measured using the data from the 2012 physics run. These observations confirm qualitatively the predictions made in the past, even if a quantitative comparison of measurements and

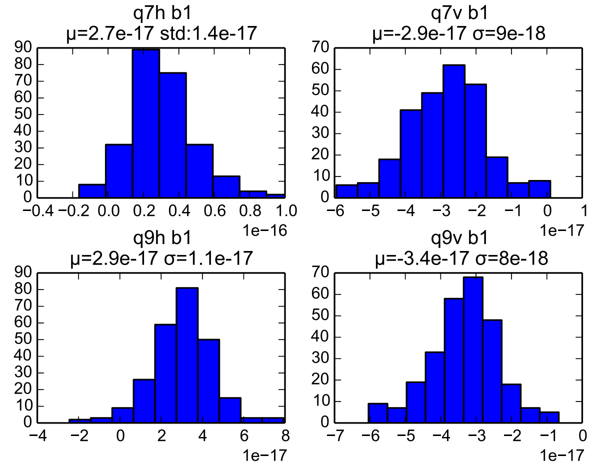

Figure 6: Histogram of the distribution of the slope of tune dependence on intensity for Beam 1. The weighted average μ and its uncertainty σ are also shown.

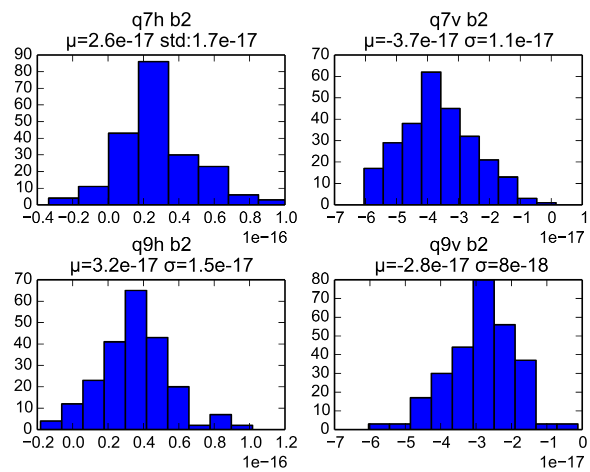

Figure 7: Histogram of the distribution of the slope of tune dependence on intensity for Beam 2. The weighted average μ and its uncertainty σ are also shown.

theoretical values is beyond the scope of this paper and will be addressed in a future study.

Although not readily available, Run I BPM data allowed to extract information for measuring the intensity-dependence effects with good accuracy. This has been made possible by extensive data mining and benchmarking among different instruments. The methods used are based on injection oscillations data for a large set of physics fills. The analysis performed and reported in this paper shows also the potential of injection oscillation data as reliable source of on-line tune measurement at injection.

ACKNOWLEDGEMENTS

We would like to thank W. Höfle, R. Steinhagen, and D. Valuch for their support and very fruitful discussions on the transverse damper, BBQ system, and related data.

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