IMPEDANCE-INDUCED BEAM OBSERVABLES IN THE CERN PROTON SYNCHROTRON

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Abstract

Impedance-induced tune shifts and instability growth rates in the CERN Proton Synchrotron are studied thanks to the recently updated impedance model of the machine. Calculation of these beam observables are obtained using both Vlasov solvers and macroparticle tracking simulations, and are compared with those observed during dedicated measurement campaigns. Thanks to improvements in the measurement procedure, including the careful monitoring of losses, bunch length, linear coupling and chromaticity, uncertainties on the tune shifts were noticeably reduced compared to previous years. Finally, the effect of linear chromaticity on tune shift slopes and growth rates has been examined, allowing for a detailed comparison with both past measurements and simulations.

INTRODUCTION

The PS impedance model has been recently updated [1] to account for the changes introduced during the Long Shutdown 2 (LS2, 2019-20). These changes were studied in detail and their effects in terms of transverse impedance computed. The next step is to assess the accuracy of the impedance model with beam-based measurements. Two impedance-induced beam observables, namely the tune shift and instability growth rate, are used to benchmark the model. The simulations are carried out with eDELPHI [2] and PyHEADTAIL [3], respectively a Vlasov solver and a macroparticle tracking code. As both methods follow radically different approaches, confidence is gained when their results agree. The beam-based measurements are performed thanks to dedicated cycles where each parameter is carefully controlled and monitored. RF parameters, bunch length, tune, chromaticity, longitudinal and transverse emittances were measured and used in the simulations, in order to be as close as possible to the measurement conditions.

TUNE SHIFT MEASUREMENTS

Tune shift measurements were performed at injection (E_{kin} = 2 GeV) and extraction (E_{kin} = 25.1 GeV) energies. The cycles used were modified versions of fixed target beams with extended plateau during which the transverse tunes were acquired. All the RF parameters as well as the optics remain the same during these plateaus in order to freeze the tunes for an extended period. The tune acquisitions span over 131,072 turns at injection energy and 65,536 turns at extraction one. The usual FFT accuracy scales in $1/N$ where N is the number of turns. Thanks to the large number of turns acquired the tune precision is expected around the 10^{-5} range, which is also the order of magnitude of the smallest expected tune shift. The horizontal and vertical chromaticities (ξ_x, ξ_y) at low energy were set to (-0.85,-1.5) in 2021 and (-0.25,-1.5) in 2022 and at high energy (0.4,0.3) in 2021 and (0.1,0.2) in 2022. The bunch length (4σ) is τ_b = 132 ns at low energy and τ_b = 52 ns at high energy.

Measurements of the horizontal and vertical tune shift vs intensity for E_{kin} = 2 GeV and E_{kin} = 25.1 GeV are presented in Figs. 1 and 2. The larger the intensity, the more likely mode-coupling may occur, and the more difficult it is to identify the most rigid mode. Moreover, in the high intensity regime, an accurate modeling of the space charge and all the non-linearities in the machine becomes necessary in order to correctly represent Landau damping effects. Hence, the maximum intensity of the scan was halved in 2022 to remain in a mostly mode-coupling free regime and to be able to compare easily experimental observations with simulations.

On one hand, the horizontal tune shift slope (i.e. the tune shift divided by the intensity per bunch) at injection energy is almost negligible. As a result, the uncertainty on the slope is nearly 20 times larger than the slope itself during 2021 measurements. The slope obtained in 2022 agrees well with the one obtained in 2021 with reduced uncertainties. The tune shift slope computed with eDELPHI returns an almost zero slope, in agreement with the measurements, while PyHEADTAIL gives a negative slope, larger in absolute value than the measurements. On the other hand, the vertical tune shift slope at injection energy is significantly larger than the horizontal one. During both campaigns the uncertainty on the slope is almost negligible and reaches less than 2% in 2022. The difference between the measured and simulated vertical tune shift slopes is less than 10% with eDELPHI and between 20% and 50% with PyHEADTAIL (for 2022 and 2021 measurements respectively). The larger discrepancy between measurements and PyHEADTAIL simulations compared to that with eDELPHI, could possibly be explained by the lack of any Landau damping (either from lattice non-linearities and/or direct space-charge) in PyHEADTAIL. The most visible mode will change whether Landau damping is included. As a result, the most visible mode during simulations can be different than the one observed in measurements. In eDELPHI all the modes can be independently observed and compared with measurements.

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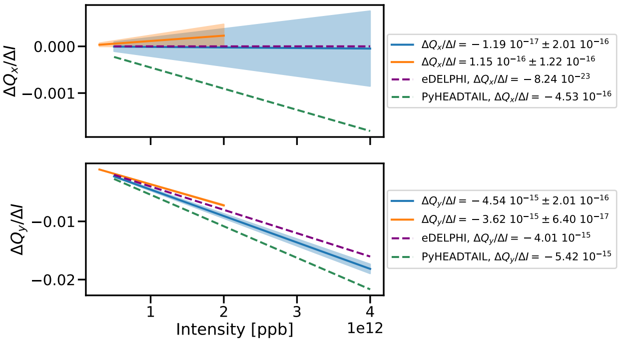

Figure 1: Horizontal and vertical tune shift vs intensity for E_{kin} = 2 GeV. The blue line corresponds to 2021 measurements and the orange one to 2022 measurements.

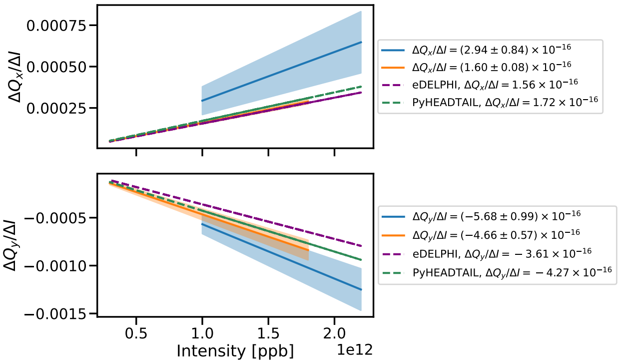

Figure 2: Horizontal and vertical tune shift vs intensity for E_{kin} = 25.1 GeV. The blue line corresponds to 2021 measurements and the orange one to 2022 measurements.

Moving from injection energy to the higher extraction energy has two notable consequences. The first one is the significant reduction of the indirect space charge impedance responsible for the previously large vertical tune shift and almost zero horizontal one, related to the elliptical shape of the beam pipe and the resulting sign of the quadrupolar impedance. The PS beam pipe geometry can be represented as an ellipse with a semi-major axis of 73 mm along the horizontal plane and a semi-minor axis of 35 mm along the vertical plane. Instead, at flat top the horizontal and vertical tune shift slopes have the same order of magnitude and are respectively positive and negative. The second consequence is a weaker direct space charge force as it scales with $1/\gamma^2$ [4]. In the case of tune shift observations, a reduced space charge results in a reduced Landau damping. Consequently, simulations not accounting for Landau damping are much more likely to be comparable to the measurements. Simulated tune shift slopes, while slightly underestimated, agree with the measured ones, especially with 2022 measurements where the discrepancy falls under 10% in both planes. The tune shift slopes measured in both planes in 2022 are noticeably smaller than their 2021 counterparts, with values outside of 2021 uncertainties. No hardware change occurred and the machine parameters are similar. The discrepancy can be caused by several mechanisms such as the transverse damper, linear coupling and non-linear chromaticity.

The first two mechanisms are studied in this paper, focusing on the injection energy scenario. In particular, during the measurements, the transverse damper is solely used to damp injection oscillations to stabilize the beam. Any use of the damper later in the cycle would perturb the betatronic oscillations if the damper cannot be considered purely resistive. The phase of a resistive damper is set to 90° in order to have an impact on the bunch orbit only and leave its phase advance untouched. Using the impedance terminology, a resistive damper acts strictly as a source of real impedance, hence does not introduce any tune shift.

Linear coupling is the result of skew magnetic components naturally present in the machine and couples the horizontal and vertical betatronic motion in the accelerator through the coupling coefficient C^-, which also represents the minimum tune separation when the horizontal and vertical tunes approach each other [5]. A qualitative assessment of the linear coupling has been done in the machine. Both tunes have been programmed to cross each other and the current in the skew quadrupoles has been varied until the smallest tune separation could be achieved. The cancellation of linear coupling was obtained for a current of 0.4 A in both even and odd straight sections skew quadrupoles.

Three scenarios are compared in Fig. 3, namely scenario A (uncorrected coupling and damper on), B (uncorrected coupling and damper off) and C (corrected coupling and damper off). Scenario C corresponds to the reference used in the measurements discussed above where the tune shift has been singled out from parasitic effects. The mechanisms perturbing the tune shifts (damper and linear coupling) are studied only on the vertical tune shift as the slope is the largest and uncertainties the smallest. By comparing scenarios A and B, the effect of the transverse damper can be assessed, showing that the modification of the tune shift slope is smaller than the uncertainties. The absence of influence of the transverse damper on the tune shift is expected from the resistive nature of the damper. Scenarios B and C can single out the effect of linear coupling. The tune shift slope increases by 30% when the linear coupling is left uncorrected. Preliminary studies with PyHEADTAIL using a single broadband resonator impedance show no significant impact of the linear coupling on the rigid mode tune shift slope. The discrepancy could still be explained by the lack of reproducibility of the measurements as it was highlighted above with 2021 and 2022 measurements.

GROWTH RATE MEASUREMENTS

Growth rate measurements were performed at flat bottom with the same cycle as the one used for the tune shift measurements. The focus is put on the horizontal plane where chromaticity ξ_x is spanning from 0 to 0.5. Growth rates for all the chromaticity and intensity values, as well as their comparisons with simulations, can be found in Fig. 4. Each growth rate was normalized by the beam intensity to better reflect the underlying mechanisms at work. The hori-

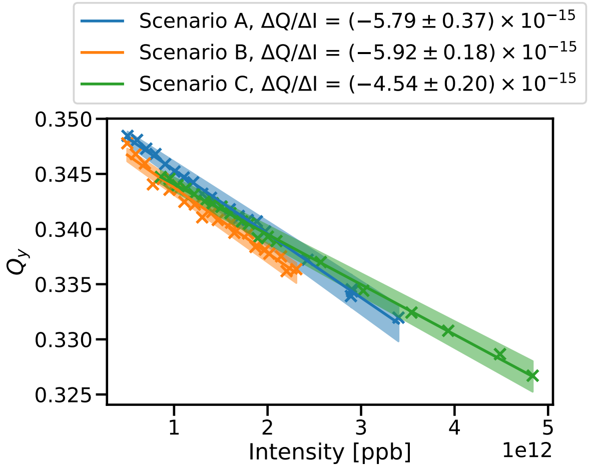

Figure 3: Impact of the transverse damper and linear coupling on tune shift measurements. Scenario A (uncorrected coupling and damper on), B (uncorrected coupling and damper off) and C (corrected coupling and damper off)

zontal emittances corresponding to the intensities 5×10^{11}, 10^{12}, 1.5×10^{12} and 3×10^{12} protons per bunch, are respectively 1.25, 1.31, 1.38 and 1.59 µm.rad. The envelope around each point represents the standard deviation of the measured growth rates when more than one measurement were acquired. Firstly, it is interesting to note that the highest normalized growth rate is obtained for the lowest beam intensity and inversely the lowest normalized growth rate for the highest beam intensity. Simultaneously, azimuthal number of the most unstable mode also tends to change with intensity by going to higher orders (i.e -1, -2, -3, etc). For each intensity, the same pattern can be observed in measurements and simulations: the growth rate increases with linear chromaticity up to a plateau, after which it starts decreasing. Up to $Q'_x \approx 3$ a qualitative agreement between simulations and measurements is obtained regarding the chromaticity value at which the growth rate is maximal. The simulated growth rate for $I_b = 3 \times 10^{12}$ protons per bunch, follows closely the measured growth rate until $Q'_x \approx 3$. Above this value, the simulated growth rates vanish for intensities lower than 2×10^{12} protons per bunch compared to the measured ones, slowly approaching 0. While simulations underestimate growth rates for the lowest intensity by a factor 2, this discrepancy decreases for higher intensities. Also, the lower the intensity the lower the azimuthal mode number. The power spectrum of a low order mode being mostly related to the low frequency part of the impedance, the discrepancy is likely to originate from this frequency range. Similarly to the tune shift measurements, no definite answer can be given without accounting for the machine non linearities and space charge.

CONCLUSION

Tune shift measurements for injection and extraction energies were performed in the PS. The measured values are

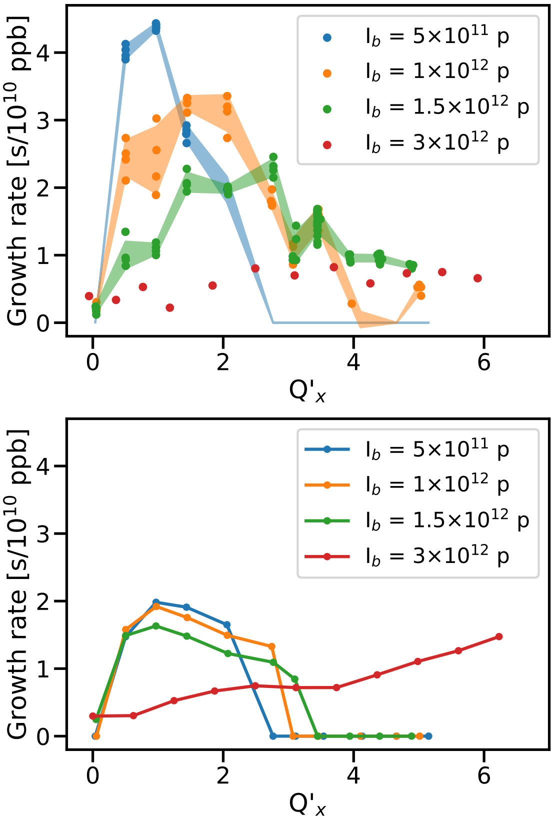

Figure 4: Horizontal growth rates vs linear chromaticity for several intensities. Top plot corresponds to measurements and bottom plot to PyHEADTAIL simulations.

compared with simulations and a fair agreement is found, especially in the vertical plane. The effect of the PS transverse damper is studied and its effect on the tune shift slope appears to be negligible. The linear coupling effect on the other hand, while being greater than the uncertainties, might be linked to the poor reproducibility of the measurements, as preliminary simulations show the lack of effect of the linear coupling on the tune shift slope. Further studies including space charge and machine non-linearities are needed to give a definite answer whether the model is able to accurately describe the machine behaviour. Finally, normalized growth rate measurements at injection energy in the horizontal plane were presented. The measurements show the different intensity regimes in the PS and exhibit a counter-intuitive behaviour with intensity, as larger bunch charge lead to lower growth rate at small chromaticity. The simulations are able to qualitatively reproduce the growth rate pattern with chromaticity for various intensities. However, apart from the high intensity case, a discrepancy of around a factor of two remains.

ACKNOWLEDGEMENTS

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