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STUDIES OF HORIZONTAL INSTABILITIES IN THE CERN SPS

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Abstract

In the framework of the LHC Injectors Upgrade (LIU), beams with double intensity with respect to the present values will have to be successfully accelerated by the CERN Super Proton Synchrotron (SPS) and extracted towards the Large Hadron Collider (LHC). However, first experience running with intensity higher than the nominal LHC beam has shown that coherent instabilities in the horizontal plane may develop, becoming a potential intensity limitation for the future high intensity operation. To understand the mechanism of these instabilities, the PyHEADTAIL code has been used to check if the SPS impedance model reproduces the observations. The instability growth rates have been studied for different machine models and different chromaticity settings. In addition, the effect of other stabilizing methods, like the octupoles and the transverse damper, has also been investigated. Measurements are presented to benchmark the simulations.

INTRODUCTION

To achieve a higher rate of collisions in the LHC experiments CERN started the High Luminosity LHC (HL-LHC) project [1]. The target is an intensity roughly twice as high as the current one. Besides upgrades in the collider and its experiments, all the injectors have to be upgraded as well in order to be able to reach the increased demands in terms of beam brightness and intensity. This is done in the framework of the LIU.

This paper focuses on the SPS, the last accelerator in the LHC injector chain. Of its two transverse planes, so far mainly the vertical plane has been studied as the dominating instabilities were developing there. But in recent high intensity multi-bunch runs in the SPS horizontal single-bunch instabilities occurred which are currently being studied and characterized. As these instabilities could be a potential issue for the LIU, a campaign to validate the horizontal impedance model has been extended to study instabilities occurring for high intensities in the horizontal plane.

Therefore, beam dynamics simulations have been performed to study unstable behaviors and possible limitations. The simulations were done with the PyHEADTAIL [2] code developed at CERN. It is using the impedance model of the SPS which has been already validated by measurements [3]. This paper presents the current status of the studies and only refers to the Q20 SPS optics which is the nominal optics at the moment and for LIU [4].

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SIMULATIONS

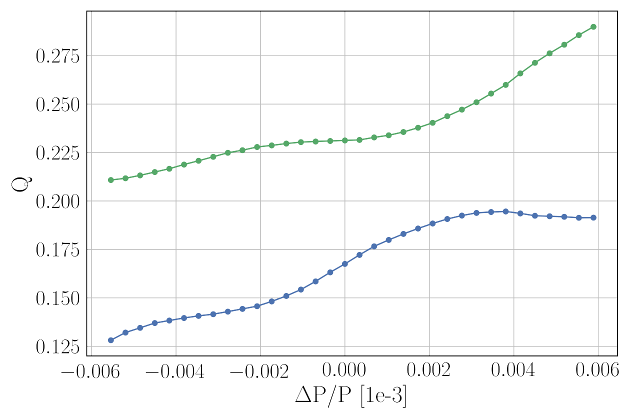

Figure 1: Measured fractional tune in the Q20 optics in horizontal (blue) and vertical (green) plane. The tune is plotted over the relative momentum error. The beam was set up to achieve a wide $\Delta P/P$ span. Every dot represents a measured value averaged over multiple shots.

First scans over Q'_x have been done using a linear and a non-linear optics model of the SPS. In the linear case all the higher order terms of chromaticity are set to zero and only linear synchrotron motion is assumed. For the non-linear case the higher order chromaticity is set to values close to measured ones shown in Fig. 1. As there is no coupling between the transverse planes activated in the simulation, the vertical plane is neglected here. This is a valid assumption as coupling between these planes is indeed negligible in the SPS. Simulations are done in single bunch mode. The intensity is set to $2 \cdot 10^{11}$ protons per bunch (ppb) and the longitudinal emittance to 0.35 eVs, i.e. the nominal SPS value at injection.

In Fig. 2 the results of the beam dynamics simulations for the linear case are shown. For negative chromaticity, the expected mode 0 head-tail instability is observed. Between a Q'_x of 0 and 5, an area with higher growth rates develops. These can be attributed to a mode 1 instability as shown in Fig. 3. The non-zero rise-time at zero chromaticity is due to the fact that the used intensity and longitudinal emittance lie in a region of weak horizontal coupling between mode -1 and 0 as described in [4]. Using the more realistic non-linear machine model for the simulations changes the growth rate development (as seen in Fig. 4). Instead of being damped by Q'_x of 0 as in the linear case, the mode 0 needs a Q'_x larger than 1 to be suppressed (see Figs. 2 and 4 blue curves). This can be expected due to the higher order chromaticities in the

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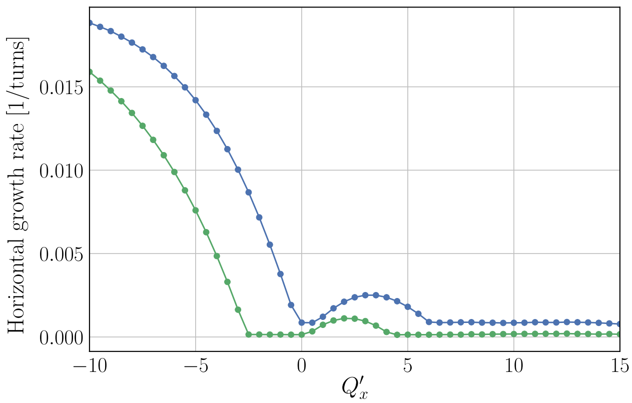

Figure 2: Simulated chromaticity scan for the linear machine model. The horizontal instability growth rate is plotted over Q'_x. The simulations have been run without (blue) and with active bunch-by-bunch damper with a damping time of 100 turns (green).

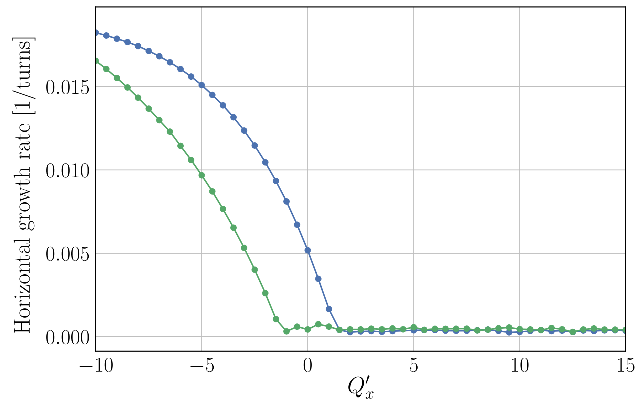

Figure 4: Simulated chromaticity scan for the non-linear machine model. The horizontal instability growth rate is plotted over Q'_x. The simulations have been run without (blue) and with active bunch-by-bunch damper with a damping time of 100 turns (green).

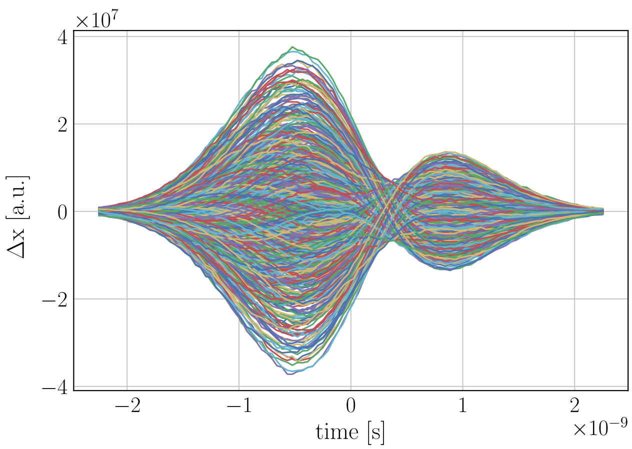

Figure 3: Simulated horizontal mode 1 instability developing for a Q'_x of 3. The amplitude of the instability is plotted over time with respect to the center of the bucket over 2000 consecutive turns.

machine (Fig. 1). The growth rate does not show big variations for higher chromaticity values any more. Especially the little bump around $Q'_x = 3$ is not observed any more. The mode 1 instability shown in Fig. 3 can still be observed but with marginal growth rates thus it is not visible in Fig. 4. The non-linear chromatic detuning of the machine reduces the instability growth rates.

Damper

For both, the linear and non linear model, simulations with an active damper have also been performed to try to cure the observed instabilities (see Figs. 2 and 4 green curves). The damping time has been set to 100 turns. Simulations show that the damper acts very efficiently on the mode 0 instability seen at negative chromaticities. For both models the bunches can be kept stable for small negative chromaticity values as long as the growth rate is lower than 1/100 turn.

For the linear case it is interesting to observe that the damper mitigates the bump of the mode 1 instability for chromaticity values larger than 2, but does not completely suppress it (see Fig. 2). This is expected as the damper cannot act on intra-bunch motion. For the non-linear case with damper (Fig. 4) the mode 1 instability can again be observed around a Q'_x of 3 with marginal growth rates.

MEASUREMENTS

A chromaticity scan was performed in the SPS using a single bunch. The scan has been done to validate the SPS impedance model. That is why the chosen bunch intensity was $2 \cdot 10^{10}$ ppb and thus a factor 10 lower than simulated above. For this measurement the growth rate evaluation was only possible for negative chromaticity values. In Fig. 5 the measured values are compared to the growth rates of a simulation employing the non-linear model and the measured bunch intensity. The simulated growth rates are close to the measured ones. The small difference can be attributed to the fact that the Q'_x is trimmed indirectly and the values presented here are linearly extrapolated from a reference measurement presented in [5]. Also marginal amplitude detuning that could occur in the machine and is not considered in the simulation could have an influence, as well as small divergences in the models for the simulations. The mode 1 at a chromaticity of 3 discussed before is neither observed in measurements nor in the low intensity simulations. As stated before its growth rate is very small and for the case of lower intensity, the instability is not observed in the given time.

When comparing the low (Fig. 5) and high (Fig. 4) intensity simulations further, it is interesting to observe that the growth rate is around a factor 10 higher for an intensity which is tenfold. The growth rate thus scales linearly with the intensity. This is expected as no mode coupling is occurring. During the measurements the Headtail-monitor installed in the SPS has been used to observe the mode 0 developing for negative chromaticity as shown in Fig. 6.

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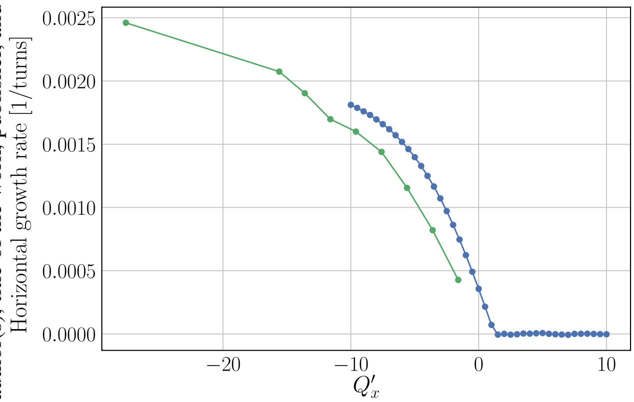

Figure 5: Comparison between measured (green) and simulated (blue) chromaticity scan. The horizontal instability growth rate is plotted over Q'_x. Every dot represents a simulation / measured value averaged over multiple shots.

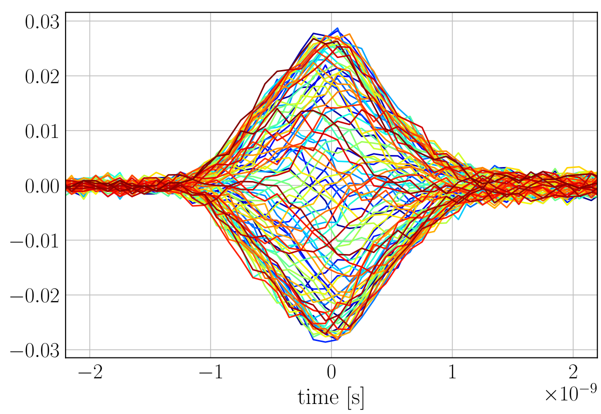

Figure 6: Measured horizontal mode 0 instability developing for a Q'_x of -6. The amplitude of the instability is plotted over time with respect to the center of the bucket over 100 consecutive turns.

Octupoles

Octupoles damp an instability by introducing a betatron tune spread as a function of transverse particle oscillation amplitude. This tune spread leads to Landau damping, mitigating the instability. A magnetic octupole scan has been done in the machine. Again a single bunch with $2 \cdot 10^{10}$ ppb was used. Q'_x was set to -2 to produce the mode 0 instability as shown in Fig. 6 which should then be mitigated by the octupoles.

As in the SPS the octupoles next to the focusing quadrupoles have the strongest effect on the horizontal plane, they were used during the measurement. Their magnetic strength (K) was changed to see the effect on the beam. The results of the measurement are plotted in Fig. 7. The measurement shows that for absolute values of K larger than 6 m^{-4} the mode 0 is not growing any more and therefore the beam is stabilized by the octupoles.

Comparing the measurements; from Fig. 5 the measured growth rate for Q'_x = -2 without active octupoles can be estimated to around 0.0005/turn, the one observed in the octupole scan measurement (Fig. 7) with the same scenario (K = 0 m^{-4}) shows a value of around 0.0003/turn. This difference can be attributed to the measurement inaccuracy. Simulations reproducing these measurements are ongoing.

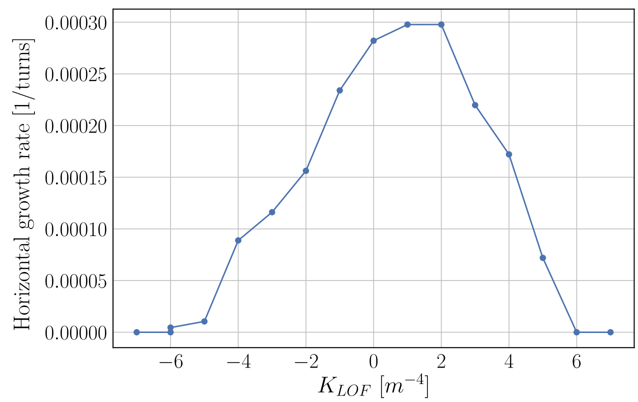

Figure 7: Measured magnetic octupole scan. The horizontal instability growth rate is plotted over the magnet strength of the octupole familiy next to the focusing quadrupoles K_{LOF}. Every dot represents a measured value averaged over multiple shots.

It is planned to remeasure all these presented scans with bunch intensities of $2 \cdot 10^{11}$ ppb and higher to check the validity of the simulations for higher intensities and to check if LIU intensities can be kept stable with the presented methods. Furthermore it is planned to try to see if the mode 1, if observed in the machine, can be damped with the octupoles.

CONCLUSION

The simulations presented in this paper show, that for higher single bunch intensities in the SPS a mode 1 can develop in chromaticity regions where it has not been observed before. The instability can be damped using higher chromaticity. Furthermore it has been shown that an active bunch-by-bunch damper can help to reduce these chromaticity values. The simulations have been validated with measurements for lower intensities.

Landau damping introduced by a magnetic octupole has also been tested as an alternative. An octupole scan showed that reasonable magnetic strength values are sufficient to damp instabilities.

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