OVERVIEW OF TRANSVERSE INSTABILITIES IN THE CERN PROTON SYNCHROTRON

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Abstract

During Long Shutdown 2 (LS2, 2019-20), the injector chain of the Large Hadron Collider (LHC) has been upgraded to reach the High Luminosity LHC goals in terms of beam intensity and brightness. In the CERN Proton Synchrotron (PS), this upgrade consisted in hardware modifications to reach a doubling of the beam intensity at extraction, while preserving the transverse emittance available from the CERN PS Booster. The gradual increase in beam intensity in the PS after the restart in 2021 brought to light several impedance-induced instabilities. One of these instabilities has been thoroughly studied in order to understand the impact of several key beam parameters (chromaticity, RF voltage, damper gain). Instabilities observations, mitigation strategies as well as comparisons with macroparticle tracking simulations will be presented in this paper.

INTRODUCTION

During the gradual intensity increase of LHC-type beams (of longitudinal emittance $\epsilon_l = 2$ eV.s), significant intensity losses could be observed towards the end of the 2 GeV plateau, before the second injection. These losses were accompanied by an exponential growth of the horizontal beam centroid position. They were reproducible from one cycle to the other and prevented the machine from reaching LIU intensity goals [1]. These losses had not been observed before LS2. The transverse damper was activated but was unable to prevent the losses even after further increasing its gain. It was also noticed that the losses started once the 10 MHz cavities voltage was lowered from 20 kV to 10 kV. The main motivation behind this RF voltage reduction was an attempt to lengthen the bunches and thus relax space charge, allowing for a more efficient transverse emittance preservation [2]. A measurement campaign took place aiming at characterizing the instability, identifying and testing mitigation strategies. The main constraint for each mitigation strategy, apart from being able to suppress the instability, is to keep the transverse emittance blow-up to a minimum.

INSTABILITY CHARACTERIZATION

In the PS, the bunch centroid and intra-bunch motion can be observed by means of a wide-band pick-up. This device allows acquiring the longitudinal and transverse motion within a specified time interval spanning between a single bunch length to a bunch revolution period. Observing in parallel the longitudinal and transverse motions allows us to identify the number of nodes in the transverse pattern, as well as a potential asymmetry between the head and the tail. The longitudinal and transverse motions of a bunch at the beginning of the exponential increase of the beam centroid were measured with the wide-band pick-up with 50 acquisitions every 3 turns.

Focusing on the only unstable bunch (the last bunch out of the four-bunch train), the intra-bunch motion can be acquired (see Fig. 1) and compared with Sacherer's theory [3] prediction. The intra-bunch signal is obtained by computing the ratio of the horizontal signal over the longitudinal one to remove the bunch profile contribution from the signal. Furthermore, a low-pass filter is applied on the resulting signal to remove sharp and fast oscillations due to noise. The superimposed traces form an envelope without any visible node along the bunch. Besides, several oscillations are observed in each trace, sign of a non-zero chromaticity. Dedicated chromaticity measurements in the machine indicated indeed a positive chromaticity around $\xi_x = 0.15$. From Sacherer's theory, below transition and without transverse damper, an unstable mode 0 is expected for a small positive chromaticity. A mode 0 instability translates into a transverse oscillations envelope without any node, similarly to experimental observations. Moreover, the intra-bunch frequency of oscillations (also referred to as head-tail phase shift) corresponds to the chromatic shift frequency:

$$\omega_\xi = \frac{\omega_0 Q_0 \xi}{\eta},$$

where $\xi = \frac{\Delta Q/Q_0}{\Delta p/p}$ is the linear chromaticity and η is the slippage factor. Nevertheless, a discrepancy between theory and measurements is observed when comparing the intra-bunch frequency of oscillations with the chromatic shift frequency. From its formula, the expected chromatic shift frequency ($|f_\xi| = \frac{|\omega_\xi|}{2\pi}$) is around 6 MHz whereas the measured intra-bunch frequency is close to 30 MHz. A factor five discrepancy is observed, which indicates that the head-tail phase shift does not originate mainly from linear chromaticity, thus leaving Sacherer's theory insufficient to study this specific instability.

The fact that the last bunch of the RF train exhibits an unstable behaviour may suggest the presence of a coupled-bunch instability. To check this hypothesis, only the fourth bunch was injected into the machine; this led to an instability as well, thus ruling out the coupled-bunch origin of the instability.

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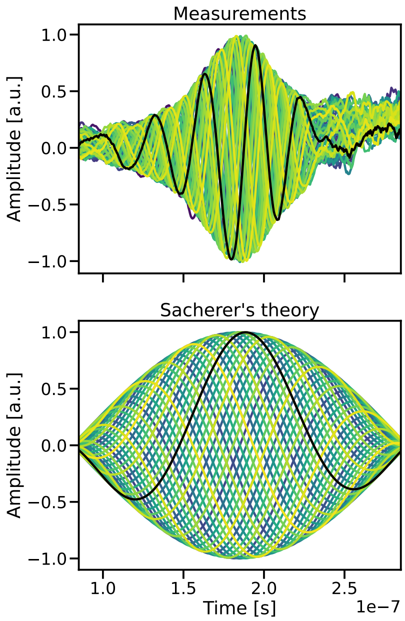

Figure 1: Intra-bunch motion of the unstable bunch (last bunch of the RF train), 50 superimposed traces and last one in black. Comparison between measurements and Sacherer's theory.

The reason why this single-bunch instability solely occurs on the last bunch of the train was then investigated. The PS bunches originate from the PS Booster (PSB) which consists of four stacked rings, each injecting one bunch into the PS during its first injection. Each ring is independent from the others, therefore each bunch has specific intensity, as well as transverse and longitudinal emittances. Supposedly, the instability only targeting the fourth bunch could be either linked to a set of beam parameters specific to the PSB ring from which it originates or from the PS RF bucket location it is injected in. The PS optics and RF parameters are the same, irrespective of the bucket number or bunch location for each bunch along the ring. However their transverse and longitudinal emittances can vary as they experience different trajectories during the PSB extraction or PS injection. As a result, phase or injection mismatch blows up the longitudinal or transverse emittance respectively. Two PSB rings were studied, namely R1 and R3. R3 corresponds to the ring on the same level as the PS and requiring minimum trajectory bending during extraction or injection, and it provides the first bunch injected during a PS injection. R1, on the other hand, is the highest ring in the PSB, thus needs the strongest bending from the kicker magnets during extraction or injection. It gives also the last bunch injected during a PS injection. After injecting only one bunch from the PSB at a time and measuring its transverse and longitudinal profiles, it was found that the profiles from R1 and R3 are almost identical. Therefore, the different instability intensity thresholds between R1 and R3 cannot be related to their transverse and longitudinal profiles. This discrepancy remains a subject of investigation.

MITIGATION STRATEGIES

The transverse damper was on when the instability was first observed and then characterized. Despite changing its gain, the damper was insufficient for suppressing the instability. As explained previously, the instability appeared following a RF voltage decrease of the 10 MHz cavities. Ramping down the RF voltage from 20 kV to 10 kV monotonically decreases the instability intensity threshold, defined as the intensity above which the instability can be observed and causes beam losses (see Fig. 2). While keeping a 20 kV RF voltage can raise the instability intensity threshold, the main motivation behind keeping a low RF voltage was a better preservation of the transverse emittance from the PSB. The LIU goals being a twofold increase of the beam intensity while preserving the transverse emittance blow-up to a minimum, raising the RF voltage seems inadequate. Another solution, inspired by the positive chromaticity measured during the instability characterization, is to bring the linear chromaticity to negative values in order to stabilize the headtail mode 0 below transition (see Fig. 2). A monotonic upward trend is observed when lowering the chromaticity down to $\xi_x = -0.3$. For this chromaticity value, instability intensity thresholds similar to the $\mathrm{V_{RF}} = 20$ kV case can be obtained. The main difference compared to the RF voltage mitigation strategy, lies in the better transverse emittance preservation.

Brightness plots are commonly used as a beam quality metric at CERN. They express the mean transverse emittance as a function of the beam intensity. LIU goals can be expressed as a brightness line in the PS. It is important to note that the transverse emittance in the PSB is not independent from the beam intensity. As intensity increases, so do space charge effects leading to a transverse emittance blow-up. The resulting brightness plot for the PS flat bottom, including or not the chromaticity trim discussed above, can be observed in Fig. 3. Without the chromaticity trim, the LIU intensity goal could not be reached because of the flat bottom instability. After modifying the chromaticity, the transverse emittance was measured to confirm the chromaticity trim had no impact on them. Finally the intensity was pushed to the highest value possible with the chromaticity trim, showing the LIU intensity goal can be exceeded.

COMPARISON WITH SIMULATIONS

All the previous measurements were performed in the presence of the transverse damper. In order to reduce the complexity of the problem and try to compare simulations with measurements, a new set of measurements has been carried out without the transverse damper and in single bunch operation. The harmonic number was set to 7 and the sum of all cavities voltage at 10 kV, leading to a Gaussian beam whose bunch length (4σ) is 208 ns. The working point was located at $(Q_x, Q_y) = (6.225, 6.24)$. The chromaticity at which the instability was first observed ($\xi_x \approx 0.1$) is chosen as the reference for the measurements. Moreover, they were performed with three out of the four PSB rings (R1, R2 and

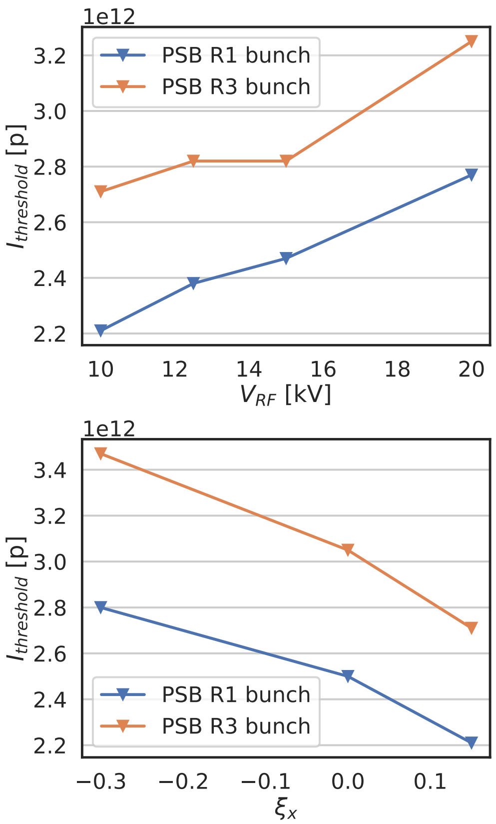

Figure 2: Instability intensity threshold (in protons for a single bunch) with respect to chromaticity (bottom) and 10 MHz cavities RF voltage (top) for the PSB rings R1 (last PS bunch) and R3 (first PS bunch).

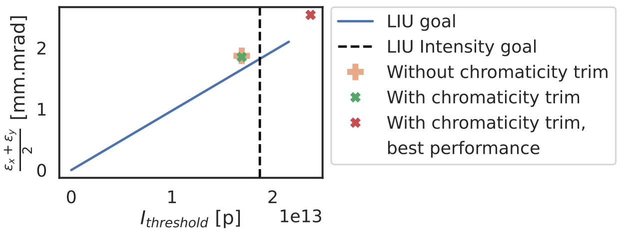

Figure 3: Brightness measurements with and without the chromaticity trim with six bunches (nominal configuration). The chromaticity trim does not affect the beam transverse emittance yet allow to push the intensity while remaining instability free.

R3) from which PS bunches are injected, as the different instability intensity thresholds were observed for bunches originating from different rings (see above). The measured growth rates are obtained by fitting an exponential growth of a BPM bunch centroid signal once an instability is observed. The procedure is repeated for increasing intensities ranging from 1×10^{11} to 2.7×10^{12} protons. Results are summarized and compared with PyHEADTAIL [4] simulations in Fig. 4.

The range between $1{\times}10^{11}$ and $1.4{\times}10^{12}$ protons includes most measurements. Reaching higher intensities translates into higher losses as well. A similar linearly increasing trend until 10^{12} protons followed by a plateau is observed among all the rings. Simulations are able to qualitatively reproduce the trend but fail at reproducing the growth rate values, underestimating them by approximately a factor two. The same factor two could be observed during the impedance-induced observables measurements campaign [5] with the horizontal growth rates at injection energy. Growth rates measurements at high intensities (>1.4×10^{12} protons) were carried out for only one ring, R1, due to radio-protection constraints. Note that growth rates measured in R1 for high intensities show a significant spread. In the end, the discrepancy between measurements and simulations could come from e.g. space charge or a missing impedance source, and is currently being investigated.

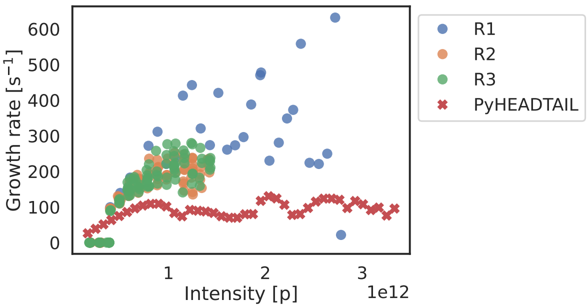

Figure 4: Growth rates vs intensity for R1, R2 and R3 bunches for $\xi_x = 0.15$ compared with PyHEADTAIL predictions.

CONCLUSION

An horizontal instability was observed during the gradual beam parameter ramp-up of LHC type beam. As a part of its characterization, its intra-bunch motion was acquired and compared with Sacherer's theory. It showed no node along its envelope, similarly to a mode 0 instability with Sacherer's theory, but showed a head-tail phase shift five times higher than the one arising from the chromatic frequency shift. Two mitigation strategies were tested in the machine: an RF voltage increase of the 10 MHz cavities, and a chromaticity reduction. While both methods were efficient at raising the instability intensity threshold, only the chromaticity reduction could preserve the transverse emittance of the beam. Finally the transverse damper was turned off in order to reduce the problem complexity and being able to compare it with simulations. At low intensities, the growth rate behaviour with intensity could be reproduced qualitatively with simulations but not quantitatively. Simulations tend to underestimate growth rates by approximately a factor two. Further studies are ongoing to explain this discrepancy by studying the effect of space charge or a missing impedance source.

ACKNOWLEDGEMENTS

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