

SOURCE OF HORIZONTAL INSTABILITY AT THE CERN PROTON SYNCHROTRON BOOSTER

E. Koukovini-Platia*, M. J. Barnes, H. Bartosik, G. Rumolo, L. Sermeus, C. Zannini
 CERN, 1211 Geneva, Switzerland

Abstract

The CERN Proton Synchrotron Booster (PSB) has been known to suffer from horizontal instabilities since its early operation. These instabilities appear at specific beam energies and range of working points. The source of the instability and the reason why the instabilities appear at specific energies remained unidentified. In routine operation, the instabilities have not been limiting the performance reach thanks to the horizontal feedback system. Recently, the interest in these instabilities has been sparked by the ongoing LHC Injectors Upgrade (LIU) program, as well as, the Physics Beyond Colliders (PBC) study group. Their systematic characterization has been carried out through measurements. Macroparticle simulations and analytical modeling have been applied to explain the measurements and the dependence on the kinetic energy. Finally, the extraction kicker has been unambiguously identified as the source of the instability.

INTRODUCTION

The PSB is the first circular accelerator of the CERN proton injector chain, in operation since 1972. Before the second long shutdown (LS2), it received beams with a kinetic energy of 50 MeV from Linac2 and accelerated them to 1.4 GeV [1]. The PSB delivers a variety of beams for the downstream Proton Synchrotron (PS), Super Proton Synchrotron (SPS), and Large Hadron Collider (LHC) machines, as well as, high intensity beams for the on-line isotope mass separator facility ISOLDE [2].

The beam requirements for the High Luminosity LHC (HL-LHC) [3] exceed the capabilities of today's CERN injector complex. In particular, the LIU project [4] aims to increase the LHC beam intensity and brightness by a factor of two for the HL-LHC era. Within the scope of the LIU project, the Linac2 has been replaced by a new machine, Linac4 [5,6], a normal conducting 160 MeV H^- linear accelerator. The future kinetic injection energy to the PSB will hence be increased from 50 MeV to 160 MeV [7] to reduce space charge effects [8]. The extraction beam kinetic energy will also be increased from 1.4 GeV to 2 GeV, with the exception of the ISOLDE facility that will not be upgraded but may require higher intensity per pulse in the framework of PBC [9].

A horizontal head-tail instability has been observed in the PSB in the past (see Ref. [14] of [10]). The instability, developing when the transverse feedback (TFB) [11] is not in operation, causes severe beam losses of up to 100%. Past studies indicate that a possible source might be the resistive wall

impedance [12]. Later studies [13] suggest that a large ripple in the power supply of the focusing quadrupole could be responsible for the instability. The beam coupling impedance of the extraction kickers was first suspected in [10, 14, 15] but without any measurements, simulations, or analytical studies to support the hypothesis.

Despite the numerous studies on the horizontal head-tail instability in the PSB, the true source remained unknown for many years. Moreover, the mechanism of the three instabilities [16] appearing at different energies and thus PSB cycle times, could not be identified. Although the instability is fully controlled in everyday operation by the TFB, interest on the subject has been revived in view of the LIU. In fact, 160 MeV is the energy where the instability appears for certain working points, which implies two things. First, the TFB must be active from the very beginning of the PSB cycle to be able to suppress the fast beam instability. Second, if the TFB is ineffective for even just a few ms, the choice of the working point in terms of horizontal tune can be severely restricted. Furthermore, due to the higher ejection energy of 2 GeV the question arises whether yet another critical energy for beam stability exists.

MEASUREMENTS

Measurements using a single bunch and single harmonic radio-frequency (RF) system were performed to characterize the instability at a constant energy plateau of 160 MeV in order to mimic the future PSB injection energy from Linac4. Measurements of beam losses and rise times versus the horizontal tunes were performed with and without the TFB to disentangle the losses due to the collective instability from those due to resonance crossings. The horizontal tune is varied between 4.10 and 4.45.

The results are presented in Fig. 1 for an intensity of 2×10^{12} p. In the upper plot, the losses are shown as a function of the horizontal tune. The losses reach up to 100% when the TFB is off (red points) and are more severe for tunes between 4.23 and 4.30. The maximum losses occur at $Q_x = 4.26$. Instead, when the TFB is on, no beam losses occur (blue crosses in the upper plot). In the bottom plot, the instability rise time versus Q_x is shown. The grey points correspond to the five acquisitions per tune-setting. The red points represent the mean value at each Q_x , while the error bars are given by the standard deviations. The fastest rise time is observed for a horizontal tune of $Q_x = 4.26$ and is 0.6 ms.

Figure 1 shows why it is important to suppress the head-tail instability after LS2. For certain working points, the instability develops at exactly the future injection energy of

* eirini.koukovini.platia@cern.ch

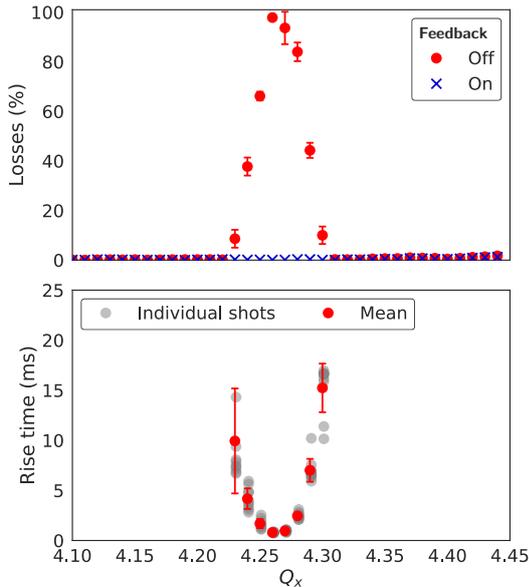


Figure 1: Measured beam losses and instability rise time versus Q_x for 2×10^{12} p. Losses reach almost 100% at $Q_x = 4.26$, and the rise time is as fast as 0.6 ms.

160 MeV. Without limiting the choice of the working point to avoid triggering the instability, the obvious requirement is that the PSB TFB should work right from injection, including during the transients of the multi-turn injection and filamentation.

An upgrade of the TFB was already envisaged for the LIU and the new hardware was installed in 2018 [17]. Thanks to the latter, it is expected that the TFB will be operational from the very beginning of the cycle and therefore be able to suppress the potential instability for tunes between 4.21 and 4.30. The new system will also be able to cope with the increased beam intensity expected in 2021 (60% increase in the PSB). Despite all the promising results on hardware testing [17], identifying the instability source remains an important task in order to improve our understanding of the underlying mechanism and to propose the implementation of permanent mitigation techniques.

SIMULATIONS

A narrow-band resonator impedance has been suspected in the past in [10, 14, 15] as the potential source of the instability. In 2010, Chanel and Carli performed vector network analyzer (VNA) measurements of the S_{11} reflection coefficient [18] on the transmission cables and kicker magnets to identify the frequencies of the resonances due to the coupling with the external circuits. This revealed three resonances at ~ 1.65 MHz, ~ 4.9 MHz, and ~ 8 MHz, suspected to be associated with the short-circuit terminations of the PSB extraction kicker.

In order to investigate if the 1.65 MHz line is responsible for the observed instability, 6D macroparticle tracking simulations with the PYHEADTAIL [19] code were performed for

comparison with measurements. The main parameters are shown in Table 1.

Table 1: Main parameters used in PYHEADTAIL.

Parameter	Value	
Circumference	C	157 m
Relativistic gamma	γ	1.17
Synchrotron tune	Q_s	1.69×10^{-3}
RF voltage	V_{RF}	8 kV
Harmonic number	h	1
Bunch intensity	N	4×10^{12} p
Resonator shunt impedance	R_s	4 M Ω /m
Resonator frequency	f_r	1.72 MHz
Resonator quality factor	Q	100
Wake decay time	N_{wake}	150 turns
Number of macroparticles	N_{mp}	1×10^6 p
Number of turns	N_{turns}	33000 turns
Chromaticity	$\xi_{x/y}$	-0.7/-1.6
Full bunch length	l_b	504 ns

The exact frequency of the narrow-band resonator, i.e. 1.72 MHz, was found by performing a fit in simulations to best reproduce the measured behavior of the instability rise time versus horizontal tune. This value is indeed close to the lowest resonance measured by Chanel and Carli and to the expectation from the beam coupling impedance model of the kicker (see Fig. 2).

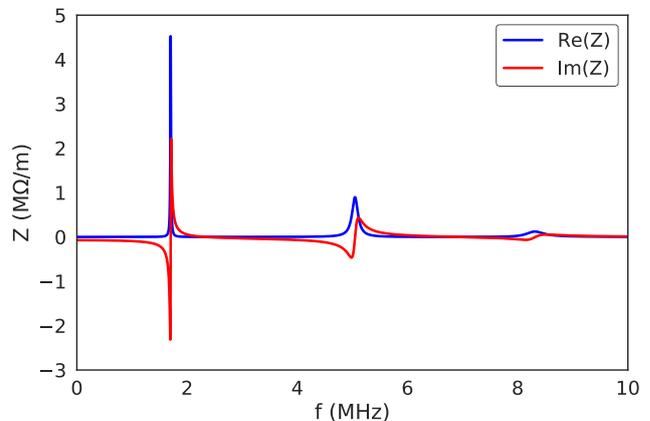


Figure 2: Horizontal impedance model of the PSB extraction kicker due to coupling with the kicker electrical circuit, including cables as coaxial transmission lines.

The impedance model of the kicker takes into account the coupling to the electrical circuit, including cables as coaxial transmission lines [20]. The frequency pattern of the resonances depends on the single-way delays and termination of the kicker circuit. The very low attenuation constant of the cables makes these resonances narrow with a Q value of about 100 and a shunt impedance in the order of M Ω /m, i.e. in very good agreement with the findings of Fig. 3.

The red points are the measured rise times with mean and standard deviation of five shots and the dashed green curve

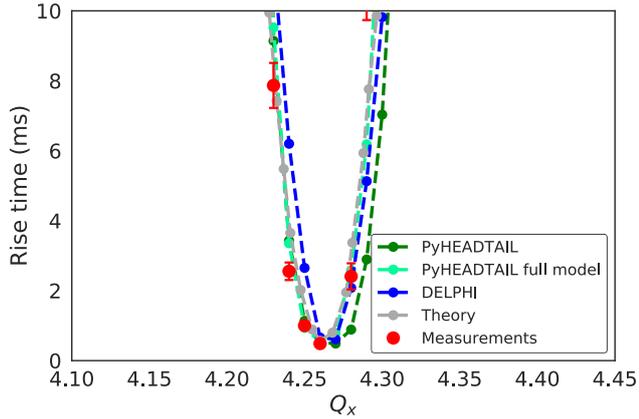


Figure 3: Rise time versus Q_x from measurements (red), PYHEADTAIL (green) and DELPHI (blue) simulations with the narrow-band resonator impedance model, and PYHEADTAIL simulations (light green) and theory (grey) with the full PSB impedance model.

corresponds to the PYHEADTAIL results using the narrow-band resonator. Evidently, the measurement results are fully consistent with the first kicker resonance at ~ 1.72 MHz. The frequency domain Vlasov solver DELPHI [21] (dashed blue curve in Fig. 3) is also used for comparison against measurements and PYHEADTAIL, and found to be in good agreement.

As a next step, the full PSB impedance model is used in PYHEADTAIL. The former also includes resistive wall impedance, indirect space charge, flanges, step transitions, injection kickers, extraction kicker magnet losses in the non-

ultrarelativistic regime [22, 23], and cavities. A good agreement was found when compared with the measurements (dashed light green curve in Fig. 3). The rise time can also be calculated from the theoretical point of view using the Sacherer theory [24] and the full PSB impedance model. The results are plotted in Fig. 3 with the dashed grey curve.

As a next step, the azimuthal mode number of the instability is investigated. In Fig. 4, the measured horizontal centroid is shown versus turns (top left), while the simulated one using the full PSB impedance model is in the top right plot. In the bottom plots, the Fast Fourier Transform (FFT) of the measured and simulated centroid signals are shown in the left and right plots, respectively. Using a sliding-window FFT, the frequency spectra are obtained at different numbers of turns, indicated by the colored vertical lines in the top plots. The FFT from the measured data indicates that the instability is of azimuthal mode number -5 (bottom left plot), in agreement with PYHEADTAIL (bottom right plot). The slight shift of the peaks away from the integer is related to the intensity.

Last, simulations are compared with measurements in terms of the radial mode of the instability. The measured head-tail modes as recorded by the horizontal pick-up in the PSB (see Fig. 5a) agree well with DELPHI simulations [25] (Fig. 5b) for a horizontal tune of 4.26. This good agreement could not be achieved without including the indirect space charge in simulations. Over the whole range of explored tunes, however, the number of nodes in the intra-bunch patterns can differ by few units, suggesting that some additional ingredient may still need to be included in the analysis.

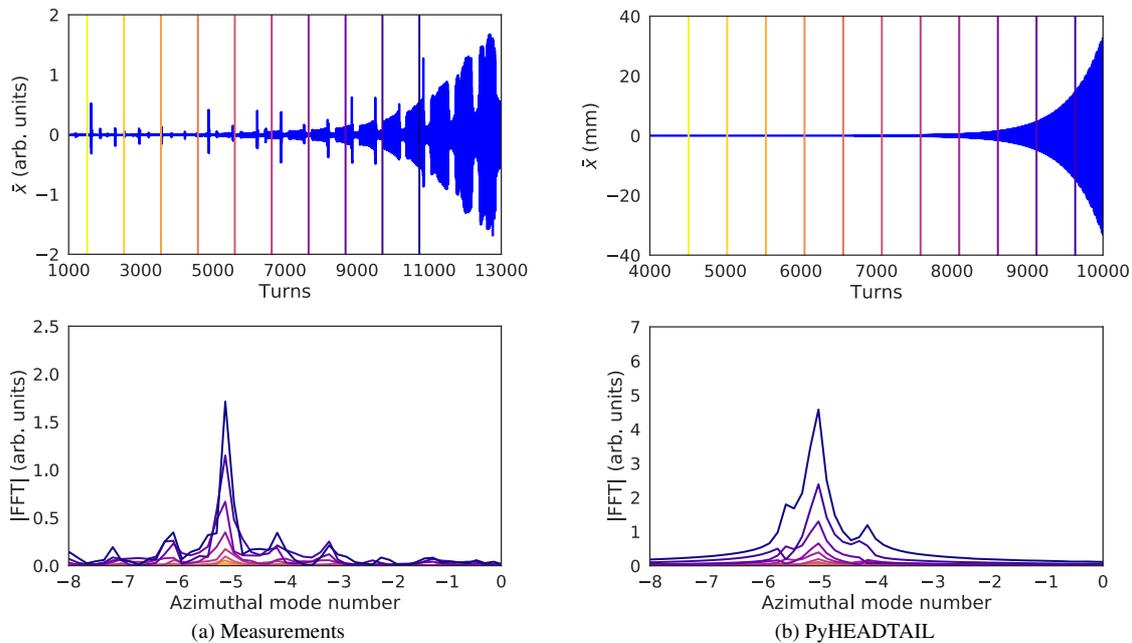


Figure 4: Horizontal centroid from measurements (top left) and PYHEADTAIL simulations using the PSB impedance model (top right). Information on the azimuthal mode number is obtained by performing a sliding-window FFT on the centroid signals. Both cases predict an azimuthal mode number -5.

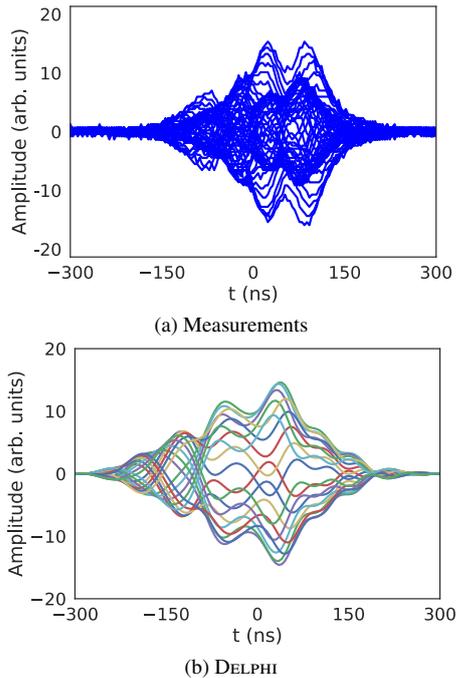


Figure 5: Head-tail modes as recorded by the horizontal pick-up for a single bunch in the PSB with $Q_x = 4.26$, $N = 4 \times 10^{12}$ p and $\xi_x = -0.7$ (top), and as predicted by DELPHI simulations for the same parameters (bottom).

ANALYTICAL STUDIES

The impedance model in Fig. 2 can also be used to predict the expected energies at which the instability will occur. The condition to drive an instability can be written as in [26, 27]:

$$\frac{f_i}{f_{\text{rev}}} + Q_x = n, \quad (1)$$

where f_i is the resonant frequency of the impedance, f_{rev} is the revolution frequency, Q_x is the horizontal betatron tune, and $n \in \mathbb{Z}$. The Q_x is varied as a function of the kinetic energy according to the ISOLDE beam operational tune settings. Figure 6 shows the left-hand side of Eq. (1) as a function of the kinetic energy for the first and second kicker resonance. All three experimentally observed instabilities along the PSB cycle [28] are predicted and explained either by the first or the second kicker resonance. The first kicker resonance is responsible for the instability at ~ 160 MeV, while the second resonance is responsible for the second and third instabilities at ~ 330 MeV and ~ 1.25 GeV, respectively. The second resonance plays a marginal role below 160 MeV because the highest significant frequency of the bunch spectrum is smaller than the resonant frequency below this energy and, hence, does not excite the resonance. For the same reason, the third kicker resonance has a minor effect all along the PSB energy range. Moreover, no further instability is predicted for energies between 1.4 GeV and 2 GeV.

Figure 6 explains for the first time why the instability in the PSB occurs only at specific energies. The revolution

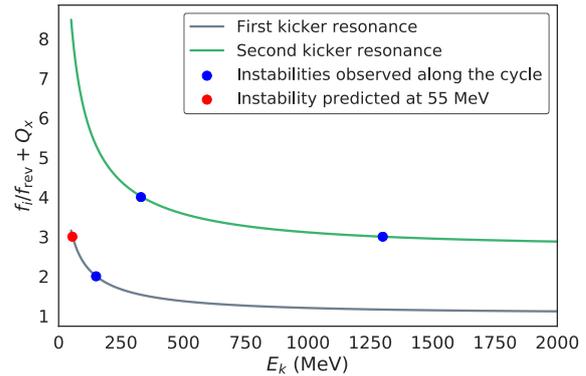


Figure 6: Left-hand side of Eq. (1) as a function of the kinetic energy up to 2 GeV for the first kicker resonance (grey line) and the second resonance (green line). The blue points mark the energies where instabilities have been observed in the PSB. The red point is a prediction that an instability should also be observed at ~ 55 MeV.

frequency, and thus the betatron frequency, changes with energy. As a consequence, the betatron tune at which the instability occurs due to a specific impedance also changes with energy. Interestingly, the theoretical analysis depicted in Fig. 6 predicts that a horizontal instability should also occur at ~ 55 MeV, which was never reported in the past. Dedicated measurements recording the horizontal pick-up signal at ~ 55 MeV were made to validate this prediction. The measured pick-up signal is shown in Fig. 7. It illustrates a horizontal head-tail signal with two nodes, recorded and observed for the first time at the energy of ~ 55 MeV.

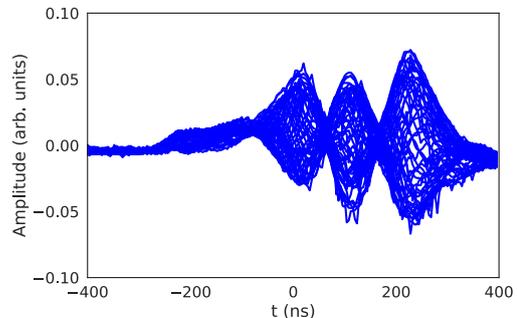


Figure 7: Head-tail mode recorded by the horizontal pick-up for a single bunch at ~ 55 MeV.

Theory and machine measurements are in excellent agreement and the dependence of the instability characteristics on the kinetic energy is fully understood. All observed instabilities along the PSB cycle can now be explained by a single source, namely the resonances due to the kicker magnets and low-loss transmission cables of the extraction kicker system.

MEASUREMENTS WITH MODIFIED KICKER TERMINATION

Measurements of beam losses versus the horizontal tune were realized with a temporary modification of the kicker's

electrical circuit. The 1 nF capacitor in one of the filter networks at the main switch end of the transmission cables of the kicker was replaced with a short-circuit. The high impedance of 5Ω at the switch end of the transmission lines was also replaced by a resistance which matches the characteristic impedance of the system (6.25Ω). The kicker system cannot be pulsed in this configuration to actually extract the beam, which was thus lost in the machine. The results from the measurements are shown in Fig. 8.

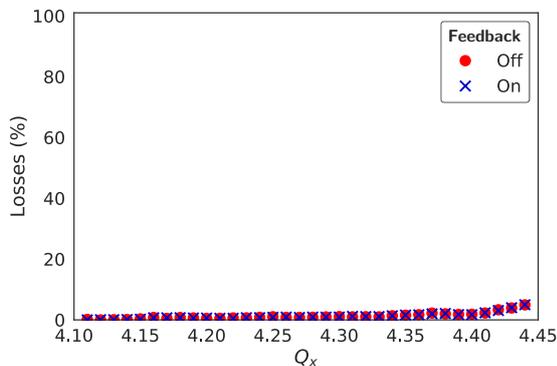


Figure 8: Beam losses at 160 MeV versus horizontal tune with intensity $N = 3 \times 10^{12}$ p with the modified kicker termination. Measurements with TFB off (red) and on (blue) are shown.

With the modified kicker termination, no sign of the instability is observed even when the TFB is kept inactive all along the cycle, as opposed to Fig. 1 with the operational kicker termination. This unambiguously confirms that the instability is caused by the high impedance at the switch end of the transmission cables to the magnets, together with the short-circuit termination of each extraction kicker magnet.

SUMMARY

A horizontal head-tail instability has been observed for more than 40 years in the PSB. Its source remained unknown until now and the instability was suppressed during routine operation by the TFB. Thanks to recent measurements, simulations, and theoretical analysis, the source of the instability has been identified. A single source, namely the resonances introduced by the cables of the PSB extraction kicker system, is found to be responsible for all the observed instabilities along the PSB cycle. Simulations and analysis with Sacherer's formalism agree with the measurement results and clearly pinpoint the origin of the instability. It is given by the high impedance at the thyatron switch end of the transmission cables to the kicker magnets together with the short-circuit termination of each magnet. With the upgrade of the TFB hardware already envisaged for the LIU, the instability is currently expected to be suppressed from the very beginning of the PSB cycle at the future injection kinetic energy of 160 MeV. Moreover, no further instability is predicted according to the theoretical analysis for energies between 1.4 GeV and 2 GeV. Ideas how to permanently suppress the kicker resonance have been considered in [29].

ACKNOWLEDGEMENTS

The authors would like to thank S. Albright, F. Antoniou, G. P. Di Giovanni, A. J. Findlay, G. Kotzian, A. Lasheen, T. Levens, E. Métral, B. Mikulec, and A. Santamaría García for the fruitful discussions and inputs to these studies. The authors are also grateful to K. Li, A. Oeftiger, and M. Schenk for providing expertise with the PYHEADTAIL code, and D. Amorim and N. Mounet for their assistance with DELPHI. Furthermore, the authors thank the BE-OP-PSB teams for their support during the experiments.

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