UNDERSTANDING OF THE NEW HORIZONTAL INSTABILITY AT THE PS BOOSTER AFTER LIU

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Abstract

Following the LHC Injectors Upgrade (LIU) project at CERN, the Proton Synchrotron Booster (PSB) has been upgraded to operate with a new injection kinetic energy of 160 MeV and an extraction energy of 2 GeV. To understand the performance of the accelerator in this new energy range, a series of measurements have been conducted, especially devoted to the beam stability to ensure the optimal operation of the machine. A horizontal instability, firstly observed in 2021 at about 1.6 GeV (between the old and the new extraction energy of the Proton Synchrotron Booster), has undergone in-depth investigation in measurements. Despite the identification of a mitigation strategy to cure the horizontal instability, efforts have also been focused to understand its source. The results have once again drawn the attention to the termination of the extraction kicker. As happened in 2018, a dedicated MD performed at the end of 2023 run with matched kicker termination confirmed the impact of the extraction kicker in this instability.

INTRODUCTION

During the Long Shutdown 2 (LS2), the LIU project was implemented to increase the beam intensity and brightness for the High-Luminosity LHC (HL-LHC) era [1]. The upgrades provide also the potential to accelerate higher-intensity beams in the framework of Physics Beyond Colliders (PBC) [2]. Particularly, at the PSB, the kinetic injection and extraction energy have been increased from 50 MeV to 160 MeV and 1.4 GeV to 2 GeV, respectively. The new energy range has highlighted the necessity for new reference measurement campaigns, in particular, to characterize the behavior of the machine in terms of beam stability. Hence, since 2021 numerous studies have been conducted [3], specifically following the observation of an unexpected horizontal instability with the transverse feedback (TFB) active at about 1.7 GeV [4]. Although instabilities were noted in the PSB from its initial operation, they did not hinder machine performance, thanks to the effective suppression by TFB. Furthermore, they were subject to a systematic study which revealed that the main driving factor behind these instabilities was the unmatched termination of the PSB extraction kickers [2]. All the observed instabilities in the machine at about 160 MeV, 330 MeV and 1.25 GeV were predicted and explained either by the first or the second kicker resonance, therefore beam-observations and model were in perfect agreement. Regarding the ongoing instability, while a mitigation strategy was identified in 2021, the underlying mechanism remained not deeply understood, as mentioned in [5], until recent studies and experimental confirmation at the conclusion of the 2023 Run, once again, underscored the involvement of the unmatched impedance cable of the extraction kicker system.

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THE NEW HORIZONTAL INSTABILITY

In 2021, for the first time, a horizontal instability was observed with a high-energy beam, at approximately 1.7 GeV, while the TFB was active, with an intensity of $500 \cdot 10^{10}$ protons per bunch (ppb). The instability mechanism was characterized with the TFB turned off, revealing that the instability occurs at even lower intensities. The instability thresholds were found to be dependent on the ring and correlated with chromaticity. Specifically, higher chromaticity values led to a slight increase in thresholds, and vice versa [5]. Observing the motion of the beam centroid at the transverse pick-up proved to be challenging, since the instability was not reproducible on a cycle-by-cycle basis. Subsequent measurement campaigns conducted each year confirmed the observations made in 2021. Furthermore, in 2022, a correlation with longitudinal emittance was identified. Particularly, higher emittance resulted in higher thresholds, and vice versa, as outlined in Table 1 and described in [3]. A mitigation strategy was identified and tested for over $1000 \cdot 10^{10}$ protons, involving the use of linear coupling and skew quadrupoles [4, 5]. However, this has the drawback of leading to larger emittances and losses downstream of the PSB due to aperture limitations. From 2022, the instability has been characterized also with the new cycles with different energy plateau. In particular, its behavior with tune has been inspected and the intensity thresholds have been observed to change with it. Notably, for specific working points, the instability has been noted to manifest

Table 1: Instability thresholds for each ring. C is cycle time. B-u off states for lower emittance, b-u on for higher emittance. Ring 2 and 4 have similar behaviour of Ring 1 and 3, respectively.

Ring	2021 (b-u off)	2022 (b-u off)	2022 (b-u on)
1	$250 \cdot 10^{10}$ ppb $C = 740$ ms	$210 \cdot 10^{10}$ ppb $C = 680$ ms	$300 \cdot 10^{10}$ ppb $C = 680$ ms
3	$350 \cdot 10^{10}$ ppb $C = 700$ ms	$380 \cdot 10^{10}$ ppb $C = 680$ ms	$530 \cdot 10^{10}$ ppb $C = 680$ ms

around 1.3 GeV, a critical energy for the instability due to the coupling with kicker cables [2]. The suspect of a potential involvement of this equipment in the instability mechanism arose again. Subsequently, a systematic characterization of the instability on an energy plateau and varying the horizontal tune was conducted [3]. The latest studies performed in 2023 are depicted in Figure 1, where beam losses and the instability rise time are the observables of interest as a function of the horizontal tune Q_x. The fine scan of Q_x, performed for the 1.6 GeV plateau cycle, clearly highlights the trend of losses and rise time, in particular one can observe a stronger behaviour of the instability (i.e. higher losses and lower rise time) for a specific value of Q_x. In the specific case, the critical Q_x is at about 0.165. Additional reference tests were performed also with 1.5 GeV and 1.7 GeV plateau cycle where the critical Q_x has been observed to increase as the energy increases, as illustrated in Fig. 2

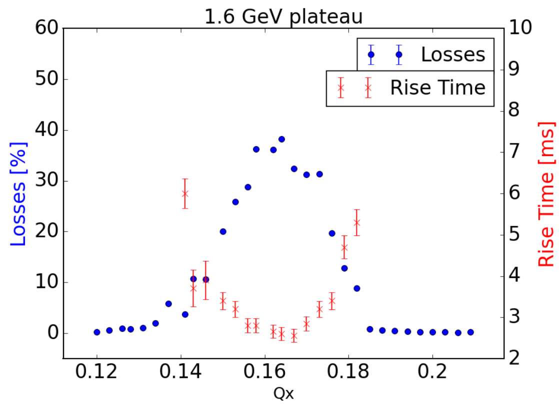

Figure 1: Measured losses (blue dots) and rise time (red dots) as a function of the horizontal fractional tune Q_x.

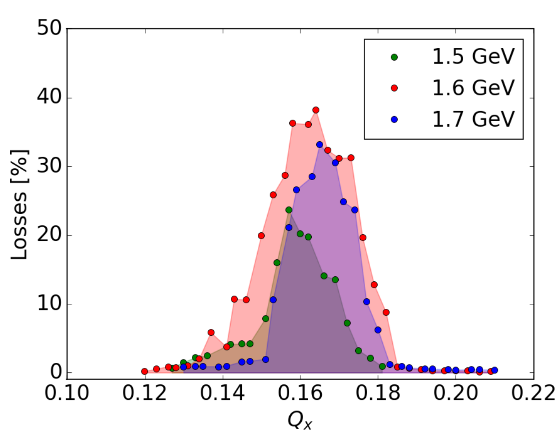

Figure 2: Measured losses as a function of the horizontal tune Q_x for the different plateau cycle.

EXPERIMENTAL VERIFICATION OF THE SOURCE

A dedicated test conducted at the end of the 2023 Run unveiled the role of the extraction kicker terminations in the instability mechanism. This test involved matching the impedance of the kicker cable terminations and subsequently repeating the instability measurements of losses and rise time as a function of Q_x, as done in the operational configuration (where the kicker terminations are unmatched). The results, in the two matching configurations of the kicker cables are depicted in Fig. 3.

The instability in the matched scenario clearly disappeared, in fact the losses are almost zero and no sign of activity of the beam centroid motion was recorded at the transverse pick-up.

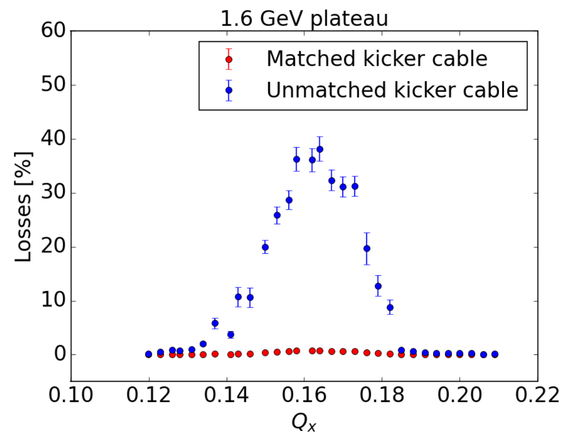

Figure 3: Measured losses with the unmatched kicker terminations (blue dots) and matched kicker terminations (red dots).

Minimal residual losses less than 1% are present but they are, with high probability, due to the non-perfect matching of the kicker termination impedance, in fact residual reflections are still observed at the kicker terminations circuit [2].

EXPECTATIONS FROM THE MODEL

Analytical studies have been conducted with an updated version of the kicker impedance model based on more precise circuit kicker information described in [6]. With the inclusion of this upgrade in the impedance model of the PSB, the Sacherer stability criteria [7] for a given operational tune and as a function of the energy can be drawn, as illustrated in Fig. 4. The criteria provides that an instability could occur each time that one of the colored lines crosses an integer. All the observed instabilities, the green crosses in Fig.4, are explained by one of the three kicker resonances, in particular the last observed instability at about 1.6 GeV is explained by the second kicker resonance. Additional instabilities, not yet observed, are also predicted below 500 MeV. Future dedicated measurements could be performed to search for these phenomena and to provide further validation of the model.

POSSIBLE CURE OF THE INSTABILITY

Different scenarios for the permanent suppression of the kicker instabilities were investigated already in [2]. A long-

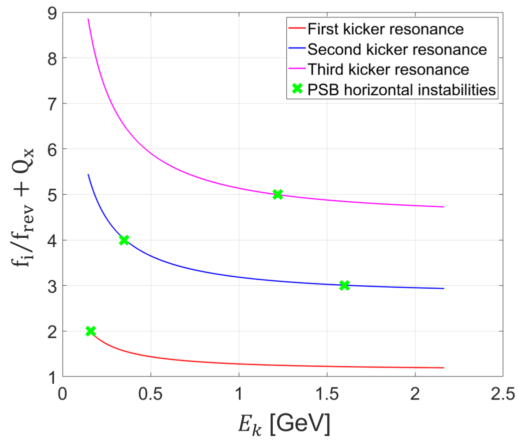

Figure 4: Sacherer stability criteria as a function of kinetic energy E_k with the updated PSB impedance model. The Q_x is varied as a function of E_k according to the beam operational tune settings. The f_i is the frequency of the impedance and f_{rev} is the revolution frequency.

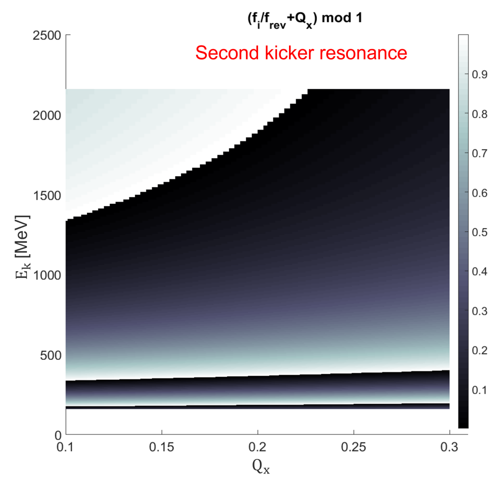

Figure 5: Sacherer stability criteria in modulo 1 as a function of Q_x and kinetic energy, considering the second kicker resonance. An instability could occur when there is a sharp transition from black to white.

term hardware solution is the introduction of a saturating inductor in the kicker circuit, studied for the suppression of the instability at the injection energy (~160 MeV). The proposed case study for this solution, has also undergone preliminary assessment for the suppression of the new high energy instability, with favorable outcomes [8]. Nonetheless, implementing such hardware modification might not be straightforward. Moreover, an operational solution, which consists in the change of working point, has also been studied through analytical computation with the model, as illustrated in Fig. 5. It predicts that an instability could occur when there is a sharp transition from black to white. Furthermore, at high energy, starting from approximately 1.3 GeV, the energy at which the instability is predicted shows significant dependence on the tune, specifically increasing with Q_x. As a consequence, the instability at about 1.6 GeV can be pushed further or even beyond 2 GeV by increasing Q_x. For instance, for a $Q_x = 0.22$, the instability would occur at ~2.1 GeV. It is worth noting that, the predicted trend of the instability with E_k and Q_x is already confirmed with the acquired experimental data, as illustrated in Fig. 2. The proposed mitigation strategy requires careful examination, particularly as higher tunes can be impacted by higher order resonances. Even though such resonances are observed in the PSB, compensation can be achieved [9]. Following the suggested approach, while compensating nonlinear resonances, tests conducted in the PSB at the beginning of the 2024 Run, have identified a new tune setting yielding highly promising and encouraging results [10]. Notably, the instability has not been observed with the TFB off for intensities up to $\approx 1.2 \cdot 10^{13}$ ppb for a fractional tune $Q_x = 0.27$. Furthermore, the transverse coupling introduced in the past is no longer necessary. This results in a great optimization of the beam characteristics in the PSB, with a smaller transverse emittance and almost perfect transmission, as outlined in Fig. 6.

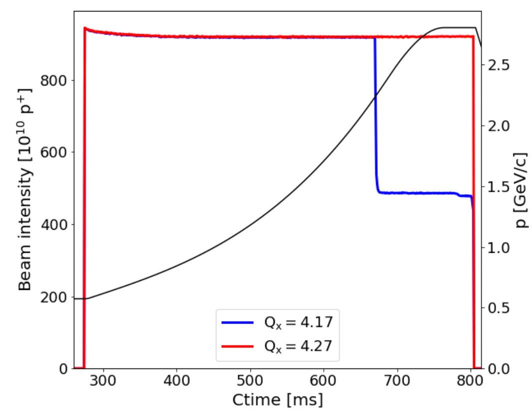

Figure 6: Beam intensity and momentum as a function of the cycle time for the two different horizontal tune, the case of 2013 (blue curve) and 2024 (red curve).

CONCLUSIONS

A horizontal instability, observed for the first time after LIU with high energy beam (~ 1.6 GeV) and the TFB on, has been investigated. Experimental tests, together with the analytical model, have confirmed the source of the instability to be once again the termination of the extraction kicker. A new tune trim function has been proposed to cure the instability operationally. First experimental tests confirm its effectiveness and have furthermore resulted in a much welcome optimization of transmission and emittance preservation in the PSB.

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