TRANSVERSE BEAM COUPLING IMPEDANCE STUDIES AT THE CERN PROTON SYNCHROTRON BOOSTER AFTER THE LHC INJECTORS UPGRADE

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Abstract

After the LHC Injectors Upgrade (LIU) project, the CERN Proton Synchrotron Booster (PSB) operates with a new injection kinetic energy of 160 MeV and an extraction energy of 2 GeV. In light of this, several measurements have been performed to characterize the behavior of the accelerator in terms of beam instability and beam coupling impedance in the new energy range. In particular, the horizontal instability observed in 2021 at about 1.7 GeV (between the old and the new extraction energy) has been deeply investigated, and betatron coherent tune shift measurements have been carried out to further benchmark the PSB transverse beam coupling impedance model. Regarding the horizontal instability, although a mitigation strategy has been identified, measurements and studies have been conducted to understand and explain its source.

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. The injector chain was prepared for the task of delivering high-brightness beams and, in this framework, the accelerator complex had been stopped to allow significant upgrades. 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 [1]. The upgrades provide also the potential to accelerate higher-intensity beams in the framework of Physics Beyond Colliders (PBC) [2]. The new energy range has led to the need for new reference measurement campaigns, in particular, to characterize the behavior of the machine in terms of beam stability and impedance budget. Instabilities have been observed at the PSB since its early operation. However, they were not limiting the performance of the machine, since the transverse feedback (TFB) was able to suppress them. The interest in stability arose due to LIU, when a horizontal head-tail instability was observed at 160 MeV, i.e. the new injection energy, for certain working points. As a result, systematic characterization was carried out through various measurements and analytical models, which suggested that the main driving factor behind these instabilities was the unmatched termination of the PSB extraction kickers. The impedance model has been used to predict the expected energies at which the instability occurred, 160 MeV, 330 MeV, 1.25 GeV. They were predicted and explained either by the first or the second kicker resonance and were in agreement with the experimental observations in the machine [2]. The experimental confirmation took place in 2018, before LS2, when instability measurements were performed with matched impedance cables of the extraction kicker system. In that configuration, no sign of instability was observed and the extraction kicker could be identified undoubtedly as the source of the instability. The instability is currently suppressed by the TFB from the injection kinetic energy of 160 MeV up to the extraction energy of 2 GeV. In 2021, a horizontal instability was observed, for the first time with the TFB active, for an intensity of $500 \cdot 10^{10}$ particles per bunch (ppb) at about 1.7 GeV [4]. Although a mitigation strategy has been identified, the mechanism is not deeply understood [5]. In addition, since the instability threshold could change with the tune, studies have been conducted to understand the source and explore if possible correlations with the past kicker instability exist. This is of relevance also for PBC, in view of the possible higher-intensity beam required for the ISOLDE facility. Measurements of the coherent betatron tune shift have been performed to refine the knowledge of the impedance model in the energy range of interest of the instability.

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TRANSVERSE BEAM-BASED IMPEDANCE MEASUREMENTS

In 2022, transverse beam-based impedance measurements have been performed in all the PSB rings during machine development studies. As a first step, measurements of the coherent tune shift have been done at 160 MeV to benchmark the pre-LS2 observations. Thereafter, measurements have been performed at 1.4 GeV and, for the first time, at 1.7 GeV and 2 GeV. As example, Figs. 1 and 2 show the results obtained at 1.4 GeV and 1.7 GeV, respectively. The formula relating the impedance to the tune shift is the following [3]:

$$\Delta Q = -\sqrt{\pi}\frac{c^2 N r_0}{8\pi^2\gamma\omega_\beta\sigma_z}\Im(Z_{\text{eff}}), \tag{1}$$

where σ_z is the r.m.s. bunch length of a Gaussian bunch with velocity $v = \beta c$, r_0 is the particle classical radius, γ is the relativistic factor, ω_β is the angular betatron frequency, and N is the bunch intensity. Z_{eff} is the transverse effective impedance defined as follows:

$$Z_{\text{eff}} = -\frac{\sum_{p=-\infty}^{\infty} Z_t(\omega')h(\omega' - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h(\omega' - \omega_\xi)}, \tag{2}$$

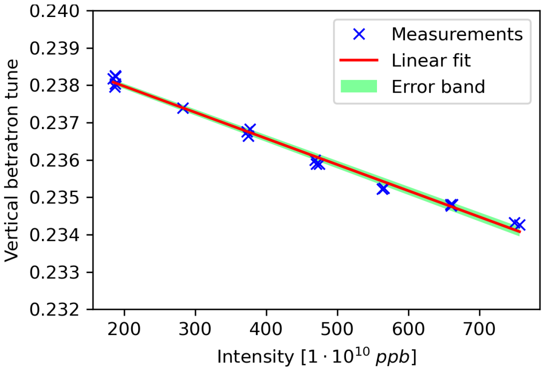

Figure 1: Vertical coherent tune shift at 1.4 GeV from beam-based measurements as a function of intensity.

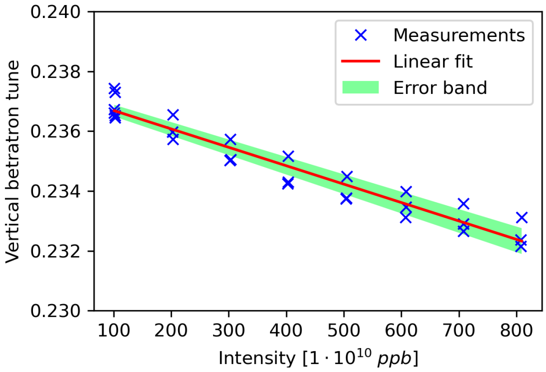

Figure 2: Vertical coherent tune shift at 1.7 GeV from beam-based measurements as a function of intensity.

with $\omega' = \omega_0(p + Q_0)$, p is an integer, Q_0 is the zero current betatron tune, $\omega_\xi = \omega_0 Q_0 \frac{\xi}{\eta}$ with ξ the chromaticity, η the slippage factor and $h(\omega) = \exp\left(-\omega^2\sigma_z^2/c^2\right)$ is the power spectrum of the Gaussian zero azimuthal bunch mode. The effective impedance obtained from the measured coherent tune shift applying Eq. 1 is displayed in Fig. 3.

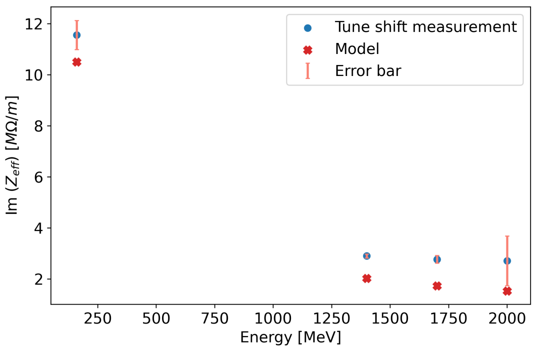

Figure 3: Imaginary vertical effective impedance versus kinetic energy. Comparison between data from coherent tune shift measurements (blue dots) and from the model (red crosses).

As expected, the impedance decreases as the energy increases, according to the indirect space charge reduction. All measurements have a good accuracy except for the one at 2 GeV, where a larger uncertainty is present. A discrepancy is found between the model and measurements, however, it is constant with energy and around 1 MΩ/m. This behavior was also observed in previous measurements and it could be an indication of a missing and/or underestimated impedance contribution in the model. The horizontal effective impedance is not discussed in this paper, because the related coherent tune shit measurements are very small, as a consequence, the measurements turn out to be rather difficult and noisy.

THE NEW HORIZONTAL INSTABILITY

In 2021, for the first time, a horizontal instability was observed with a high energy beam and the TFB active, for an intensity of $500 \cdot 10^{10}$ ppb, at about 1.7 GeV. Studies have been conducted to assess the driving mechanism behind it, however, the instability is not yet fully understood. Characterization of the instability mechanism has been carried out with the TFB off, where the instability arises for even lower intensities [5]. The instability thresholds appear to be ring-dependent and correlated with chromaticity. In particular, higher chromaticity than natural brings to a slight increase of thresholds, while lower value than natural to a significant reduction of the thresholds. Observation of the beam centroid motion at the transverse pick-up has been quite complicated since the instability behavior is not reproducible on a cycle-by-cycle basis. For the moment, a mitigation strategy has been identified and tested for more than $1000 \cdot 10^{10}$ protons and the instability is currently cured using linear coupling and skew quadrupoles [4, 5]. The measurement campaign performed in 2022 confirmed part of the observations of 2021, such as the behavior with the chromaticity and the transverse pick-up observations. However, the intensity thresholds observed in 2022 are higher compared to the ones recorded in 2021 but still ring-dependent [6]. Nevertheless, the difference has been investigated and a correlation with the longitudinal emittance has been unveiled: higher emittance leads to higher thresholds. In fact, the first measurements performed in 2022 have been conducted with the RF blow-up enabled, leading to a higher longitudinal emittance, as displayed in Fig. 4. When repeating again the same measurements with the blow-up disabled, which instead was the case in 2021, the instability thresholds have been found to be in agreement, as summarized in Table 1. Therefore, the instability behavior appeared consistent with time. In 2022, the instability has been studied also with the new cycle with a plateau at 1.7 GeV. In particular, its behavior with tune has been inspected and the intensity thresholds have been observed to change with it. In particular, the instability has been observed to arise around 1.3 GeV, one of the energies at which the instability due to the kicker cable was observed in the past. This is suggesting a possible involvement of this equipment in the instability mechanism. Following this test, a systematic characterization of the instability on an energy plateau and varying the horizontal tune has been conducted. The beam losses and the instability rise time were the ob-

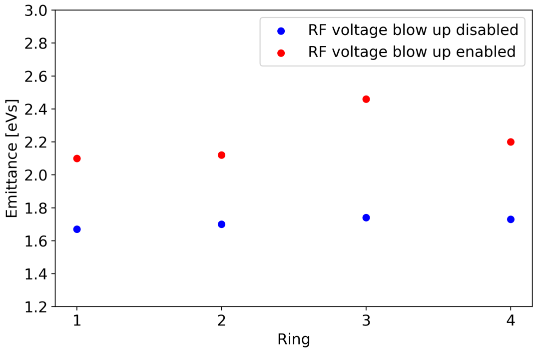

Figure 4: Measured longitudinal emittance before the instability appears, with the RF blow up (red dots) and without the RF blow up (blue dots).

Table 1: Instability intensity thresholds for each ring. C is the cycle time. b-u off states for blow-up disabled and b-u on for blow-up enabled.

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
2	$250 \cdot 10^{10}$ ppb $C = 700$ ms	$255 \cdot 10^{10}$ ppb $C = 675$ ms	$350 \cdot 10^{10}$ 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
4	$350 \cdot 10^{10}$ ppb $C = 720$ ms	$320 \cdot 10^{10}$ ppb $C = 680$ ms	$390 \cdot 10^{10}$ ppb $C = 670$ ms

servables of interest, as shown in Figs. 5, 6. In particular,

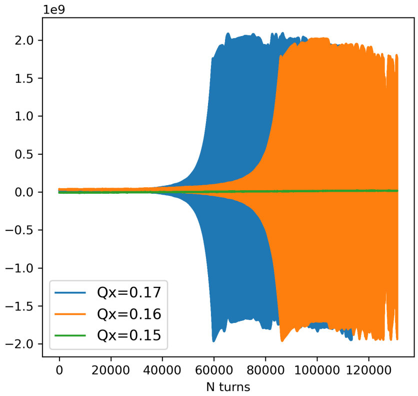

Figure 5: Beam centroid motion versus the number of turns for different values of the horizontal tune.

from the exponential fit of the envelope of the beam centroid motion over the number of turns, the rise time of the instability has been computed. From the drop in the intensity, the percentage of losses can be also derived. These quantities are summarized in Fig. 7 as a function of the horizontal tune. The instability appears between the horizontal tune values of 0.15 and 0.17, however, the measurements are affected by poor resolution in the tune scan. In fact, the possibility of having a finer scan of the tune was limited by the quite short

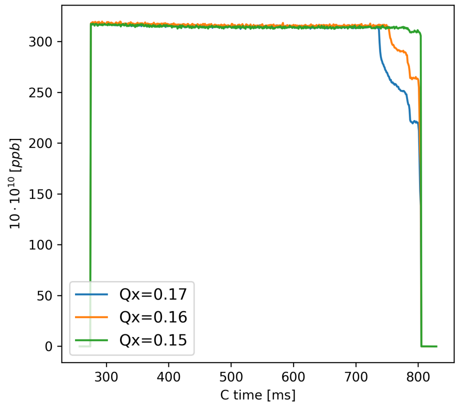

Figure 6: Beam intensity versus the cycle time for the different values of the horizontal tune.

plateau of the cycle. In this framework, future studies will focus on more detailed tune scans in order to better investigate the correlation of the instability with the horizontal tune. Moreover, the same procedure needs to be repeated with matched cables of the extraction kicker, as done before LS2 [2], to assess whether the kicker termination could be correlated with the observed instability.

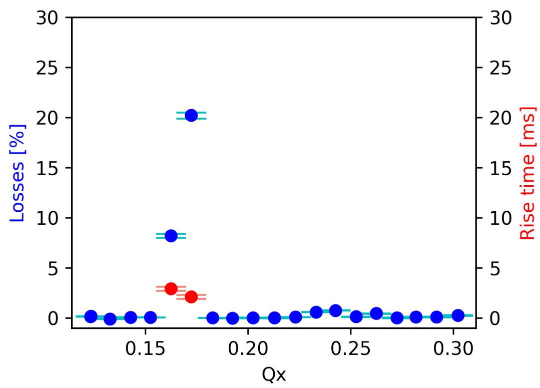

Figure 7: Measured losses (blue dots) and rise time (red dots) as a function of the horizontal tune.

CONCLUSIONS AND OUTLOOK

Transverse beam-based impedance measurements have been performed and presented for the new energy range of the PSB after LIU. According to expectations, the impedance measurements have been found to be in good agreement with the pre-LS2 measurements. On the other hand, the measurements in the unexplored energy range further confirm a missing impedance contribution of about 1 MΩ/m independent on energy. This calls for a refinement of the PSB impedance model. A horizontal instability observed for the first time in 2021 has been investigated and some differences observed with respect to the past have been outlined. Although its mechanism is not fully understood thus far, preliminary results bring again the attention to a possible involvement of the extraction kicker.

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