ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST058

STUDIES ON THE VERTICAL HALF-INTEGER RESONANCE IN THE CERN PS BOOSTER

T. Prebibaj*[1], F. Antoniou, F. Asvesta, H. Bartosik
CERN, Geneva, Switzerland
G. Franchetti[1]
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[1]also at Goethe University, Frankfurt, Germany

Abstract

Following the upgrades of the LHC Injectors Upgrade Project (LIU), the Proton Synchrotron Booster (PSB) at CERN successfully delivers beams with double brightness. An important contributing factor for this was the dynamic correction of the beta-beating induced by the injection chicane which allowed stable operation closer to the half-integer resonance. Ideally, injection above the half-integer resonance could further improve the beam brightness. In this context, a series of studies were initiated in order to characterize the effects of space charge when crossing the half-integer resonance. In this contribution, the first results of these investigations are reported.

INTRODUCTION

The brightness of the PSB beams is limited by space charge effects at injection [1]. In the framework of the LHC Injectors Upgrade (LIU) project [2], the PSB injection energy was increased from 50 MeV to 160 MeV, which allowed doubling the beam intensity while having similar space charge detuning and transverse emittances.

Stable beam operation with higher working points, that are closer to the vertical half-integer resonance $2Q_y = 9$, further mitigated the space charge effects at injection and contributed to an increased beam brightness [3]. On the same principles, injection above the half-integer resonance could result to an even higher brightness. However, the extraction working point of the PSB is set at $(Q_x, Q_y) = (4.17, 4.23)$ and thus the half-integer resonance needs to be crossed during the acceleration cycle. This can result in particle losses and/or emittance growth.

The effects of the half-integer resonance crossing on the beam will depend on the resonance strength, the crossing speed and the space charge detuning. At the end of 2021, systematic studies were initiated in the PSB to understand the beam behaviour under these conditions.

The PSB is an excellent machine for performing these studies. The multi-turn H^- injection scheme [4] allows producing a large variety of transverse emittances and beam intensities, which enables the control of the space charge tune footprint. In addition, the recently implemented tune control system [5] allows machine operation in a wide range of working points below and above the half-integer resonance and also the dynamic change of tunes along the acceleration cycle. Finally, the identification and compensation of resonances up to fourth order has been extensively studied in the PSB [6]. As a result, the half-integer resonance not only can be compensated to a good extent, but can also be excited in a controlled manner by deliberately degrading the compensation scheme.

This contribution focuses on the characterization of the half-integer resonance for different excitation amplitudes.

HALF-INTEGER RESONANCE CORRECTION AND EXCITATION

The PSB is equipped with a set of multipole corrector magnets that are used for the compensation of the naturally excited resonances. The half-integer resonance $2Q_y = 9$ is compensated by two families of normal quadrupole correctors, illustrated in Fig. 1. The first family consists of quadrupoles in the fourth and in the twelfth section of the machine (QNO412) and the second family of quadrupoles in the eighth and sixteenth section (QNO816). The driving term generated by QNO412 is orthogonal with respect to the driving term of QNO816. The optimal strength of the quadrupoles that cancels the driving term of the naturally excited half-integer resonance is determined experimentally [7]. The quadrupole families are configured such that they do not change the tune.

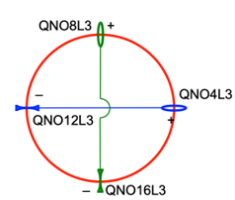

Figure 1: The two orthogonal families of quadrupole correctors and their corresponding polarities.

By slightly varying the strength of the QNO412 and QNO816, with respect to their compensating value, the half-integer resonance is excited. Since the orientation of the two families is orthogonal, the half-integer resonance can be excited with any phase and amplitude, within the limits of the quadrupole currents.

The excited resonance is characterized by its stopband width. Inside the stopband the particle motion is unstable and losses occur. Outside but near the stopband, the motion is stable but the growth in amplitude of the betatron oscillations (β-beating) can drive particles to large amplitudes

* tirsi.prebibaj@cern.ch

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST058

and thus, due to the limited machine aperture, lead to losses. Furthermore, the space charge detuning can further extend the tune region in which losses are observed.

Resonance Width Measurement

For the characterization of the stopband width, the resonance was excited by changing the current of the QNO816 family by $\delta I_{816} = -2$ A from its nominal copmensating value. In order to minimize the effects coming from the space charge detuning and the β-beating, a coasting beam with low intensity and small transverse emittances was used, shown in Fig. 2. The RMS-momentum spread was measured at $(\delta p/p)_{\mathrm{RMS}} \approx 10^{-3}$ and the maximum space charge detuning was analytically estimated [8] to be $\approx 3 \cdot 10^{-3}$.

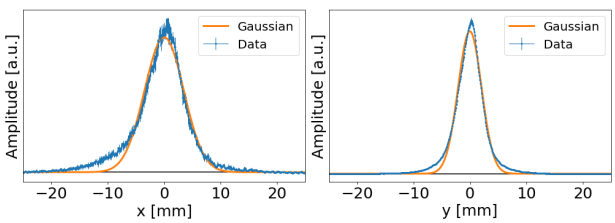

Figure 2: Horizontal (left) and vertical (right) beam profile used in the half-integer stopband width measurements. The profiles are measured with a wire scanner [9]. The asymmetric tails in the measurement are associated with the scattering of the beam due to the crossing wire [10].

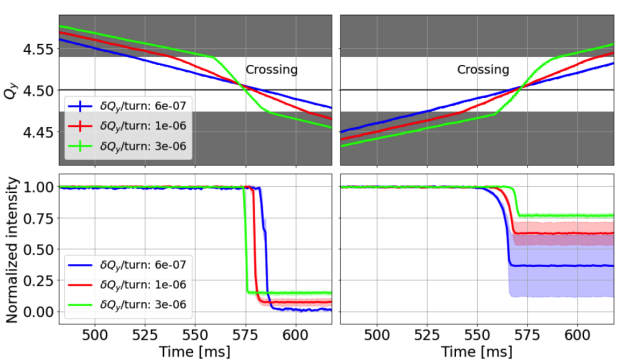

Figure 3: Evolution of beam losses when crossing the half-integer with different crossing speeds from both directions.

The stopband width δQ of the half-integer resonance $2Q_y = 9$ was measured by dynamically crossing the resonance from above ($Q_y > 4.5$) and from below ($Q_y < 4.5$) with different crossing speeds while monitoring the beam intensity. Figure 3 shows the measured vertical tunes (top) and the normalized beam intensity (bottom) evolution during the crossing of the resonance from both directions. The different colors correspond to the three different crossing speeds. The tune is measured using a Base-Band-tune pickup (BBQ system) and the intensity using Beam Current Transformers (BCT) [11]. To reduce statistical uncertainties, the intensity was measured for multiple cycles for each of the different crossings. The solid lines represent the mean intensities while the shaded areas the standard deviation (1σ).

When the beam is near the resonance, losses are recorded. The losses range between 80 – 100 % when crossing from above and 20 – 60 % when crossing from below. While the average losses are lower when crossing from below, the uncertainty of the intensity after crossing the resonance is much larger, especially for the lower crossing speeds. The reason for this is being investigated. Fewer particles are lost for faster crossing speeds, as expected.

The beam intensity for the different crossing scenarios is plotted in Fig. 4 as a function of the vertical tune. It can be observed that when crossing from below, the beam loss stops at approximately $Q_y = 4.5005$, independently of the crossing speed. Similarly, when crossing from above, the beam loss stops at approximately $Q_y = 4.4965$. At these tune values the beam intensity is stable and thus they define an upper limit of the stopband boundaries. Therefore, for this particular excitation, the stopband width should be at most $\delta Q \approx 4.5005 - 4.4965 = 0.0040$. Depending on the crossing speed, the beam spends a few thousands of turns inside the stopband.

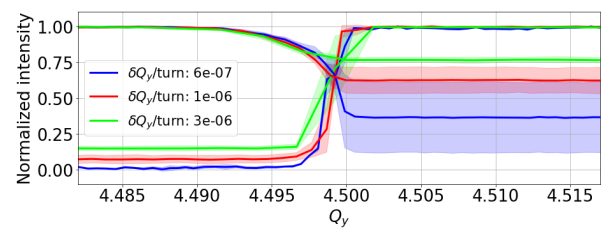

Figure 4: Half-integer stopband width measurement for $\delta I_{816} = -2$ A.

It is worth mentioning that attempts to cross even faster or even slower were made. While it is possible to apply dynamical tune changes that are faster, the intensity acquired by the BCT is limited to every 1 ms interval, in which the vertical tune changes considerably. This results to a loss in resolution of the vertical tune, making it impracticable to distinguish the upper limits of the stopband boundaries. Nevertheless, the losses are again much lower for faster crossing speeds. For dynamical tune changes that are slower, the beam is fully lost and the same analysis cannot be performed.

Analytical estimations of the half-integer stopband can be found in literature [12, 13]:

$$\delta Q_{\mathrm{an}} = \frac{1}{2\pi}\left|\oint \beta(s)p(s)e^{-(2n+1)\phi(s)}ds\right|, \qquad (1)$$

where p is the perturbation strength, β the beta-function at the location of the perturbation, n the integer part of the tune and ϕ the normalized phase advance. Considering that the half-integer resonance is perfectly compensated and the only excitation driving term comes from the $\delta I_{816} = -2$ A of the QNO816 family, this formula gives a value of $\delta Q_{\mathrm{an}} \approx 0.0012$. This width is well within the upper boundaries that were defined experimentally. Since it is impossible to have a perfect compensation of the half-integer resonance and a zero detuning from space charge, the experimental boundaries are expected to overestimate the stopband width.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST058

APPLYING STRONGER EXCITATIONS

An effort was made to measure the half-integer stopband width for different excitation amplitudes using the same method. The resonance was again crossed from both directions and the beam intensity was monitored. The results are summarized in Fig. 5. The different colors correspond to different excitation amplitudes of the resonance while in all cases the crossing speed was the same.

At the top plot of Fig. 5, the beam of Fig. 2 was used (low intensity and small transverse emittances). The points in which the losses stop while crossing the resonance, that previously represented the boundaries of the stopband, cannot be determined here since the beam is fully lost for all of the stronger excitations. Thus, it is not possible to assess the stopband boundaries like this.

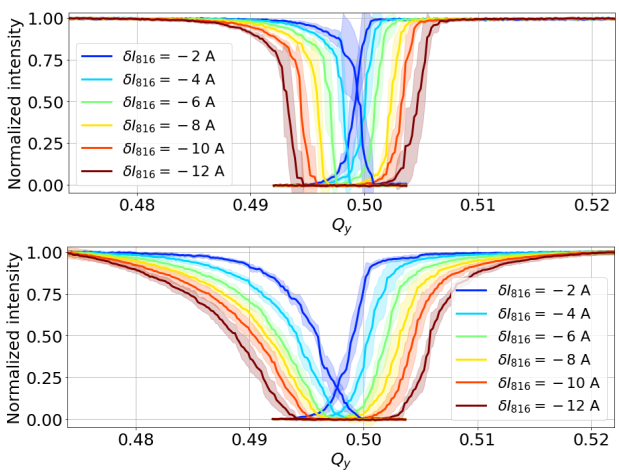

Figure 5: Beam intensity as a function of the vertical tune for different amplitudes of the half-integer excitation. In the top plot the beam of Fig. 2 was used, while in the bottom plot the beam of Fig. 6.

Instead of searching for the tune in which the beam exits the stopband and the loss stops, one could try and specify the tune in which the beam enters the stopband and the losses start. What complicates the situation in this case is that the losses, instead of abruptly starting at some tune (the tune in which the beam enters the stopband), they increase gradually over a range of tunes. This behaviour is more evident when approaching the half-integer resonance from below ($Q_y <$ 4.5) and could be associated with the β-beating.

The last argument can be further supported by the bottom plot of Fig. 5. Here, the same experiment as before was performed but with a beam that has low intensity and much larger vertical emittance. This beam, which is shown in Fig. 6, was deliberately blown-up by applying an injection misteering and enabling octupoles to induce filamentation in the transverse plane. The vertical particle distribution almost fills the acceptance of the PSB, making the sensitivity of the losses to the β-beating much higher.

The losses during the crossing that are shown in the bottom plot of Fig. 5 start much earlier than the top plot of the same figure, despite the fact that the stopband size should be the same, and are even more gradual. This can be attributed to the beta-beating as even a weak perturbation in the optics can induce measurable losses due to the large beam size.

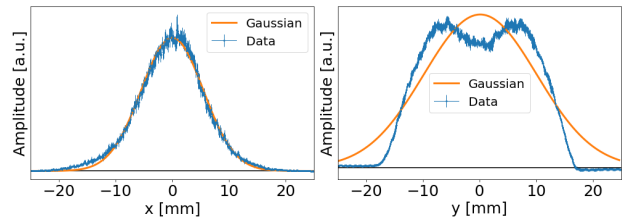

Figure 6: Horizontal (left) and vertical (right) beam profile that have been deliberately grown to fill the acceptance.

Although the stopband width cannot be strictly determined for stronger excitations, one can define the resonance width at which the losses increase above a specified threshold as a function of the excitation strength. This was only done for the low intensity and small transverse emittances (Fig. 2) to minimize the contribution of the beam loss from β-beating. Figure 7 shows the tunes at which the 5 % losses is reached for the different excitation strengths. The analytical estimation of the stopband width, using Eq. 1, is plotted with green and is always within the boundaries at 5 % losses. The dependence of the stopband width to the excitation strength is almost linear as it is expected from the analytical formula. Further simulation studies will follow in order to relate the observed differences.

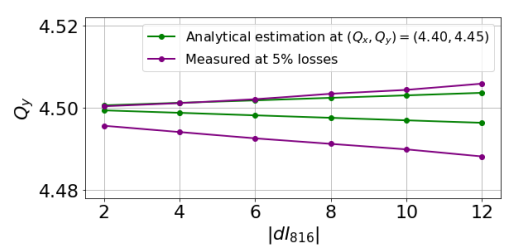

Figure 7: Tunes at which 5 % losses are observed in the top plot of Fig. 5 and comparison to analytical estimations of the stopband width.

SUMMARY AND OUTLOOK

In this contribution, attempts to experimentally characterize the half-integer resonance for different excitations are presented. For a weak excitation of the resonance, an upper limit for the stopband boundaries is determined by identifying the tunes in which the beam loss ends. For stronger excitations this is not possible because the beam is lost completely. However, the scaling of the stopband width with the excitation amplitude was measured and compared to analytical estimations of the stopband with a good agreement. The discrepances between the analytical and experimental estimations of the stopband width will be addressed with numerical studies.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST058

REFERENCES

[1] E. Benedetto, M. Cieslak-Kowalska, V. Forte and F. Schmidt, "Space Charge Effects and Mitigation in the CERN PS Booster, in View of the Upgrade", in *Proc. 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, Malmö, Sweden, Jul. 2016, pp. 517-522. doi:10.18429/JACoW-HB2016-THPM9X01

[2] J. Coupard (ed.) *et al.*, "LHC Injectors Upgrade, Technical Design Report, Vol. I: Protons", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337 2014. doi:10.17181/CERN.7NHR.6HGC

[3] T. Prebibaj *et al.*, "Injection chicane beta-beating correction for enhancing the brightness of the CERN PSB beams", in *Proc. 65th ICFA Advanced Beam Dynamics Workshop (HB'21)*, Fermilab, Batavia, IL, USA, Oct. 2021, paper MOP18, pp. 112-117. doi:10.18429/JACoW-HB2021-MOP18

[4] W. J. M. Weterings, C. Bracco, L. O. Jorat, M. Meddahi, R. Noulibos, and P. Van Trappen, "The New Injection Region of the CERN PS Booster", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2414–2417. doi:10.18429/JACoW-IPAC2019-WEPMP039

[5] F. Antoniou *et al.*, "The PS Booster alignment campaign and a new tune control implementation after the LHC Injectors Upgrade at CERN", in *Proc. 65th ICFA Advanced Beam Dynamics Workshop (HB'21)*, Fermilab, Batavia, IL, USA, Oct. 2021, paper MOP14, pp. 89-94. doi:10.18429/JACoW-HB2021-MOP14

[6] F. Asvesta *et al.*, "Resonance Compensation for High Intensity and High Brightness Beams in the CERN PSB", in *Proc. 65th ICFA Advanced Beam Dynamics Workshop (HB'21)*, Fermilab, Batavia, IL, USA, Oct. 2021, paper MOP06, pp. 40-45. doi:10.18429/JACoW-HB2021-MOP06

[7] A. Santamaría García *et al.*, "Identification and compensation of betatronic resonances in the Proton Synchrotron Booster at 160 MeV", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1054-1057. doi:10.18429/JACoW-IPAC2019-MOPTS086

[8] F. Asvesta and H. Bartosik, "Resonance Driving Terms From Space Charge Potential", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2019-0046, Oct. 2019, https://cds.cern.ch/record/2696190.

[9] R. Veness *et al.*, "Installation and Test of Pre-series Wire Scanners for the LHC Injector Upgrade Project at CERN"in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 412-414. doi:10.18429/JACoW-IPAC2017-MOPAB121

[10] T. Prebibaj *et al.*, "Characterization of the Vertical Beam Tails in the CERN PS Booster", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, paper MOPOST057, this conference.

[11] G. Gelato, "Beam current and charge measurements", in *Beam Instrumentation (Ed. J. Bosser)*, CERN, Geneva, Switzerland, Rep. CERN–PE–ED-001–92, p. 185, 1992.

[12] E.D Courant and H.S Snyder, "Theory of the alternating-gradient synchrotron", in *Annals of Physics*, vol. 3, no. 1, pp. 1-48, 1958. doi:10.1016/0003-4916(58)90012-5

[13] H. Wiedemann, "Quadrupole Field Perturbations", in *Particle Accelerator Physics; 3rd ed.*, Springer Berlin Heidelberg, New York, 2007, pp. 426-435.