CHARACTERIZATION OF THE VERTICAL BEAM TAILS IN THE CERN PS BOOSTER

T. Prebibaj*[1], F. Antoniou, F. Asvesta, H. Bartosik,
C. Bracco, G. P. Di Giovanni, E. Renner[2],
CERN, Geneva, Switzerland
[1]also at Goethe University, Frankfurt, Germany, [2]also at TU Wien, Vienna, Austria

Abstract

The CERN Proton Synchrotron Booster (PSB) went through major upgrades in the framework of the LHC Injectors Upgrade Project (LIU) aiming to double the brightness of the LHC beams. Operation restarted in early 2021, demonstrating the expected performance improvement. The high-brightness beams, nevertheless, appear to have overpopulated tails in the vertical beam profiles, both at injection and at extraction energies. In an attempt to understand the origin and evolution of the observed tails, systematic profile measurements were performed for different machine and beam configurations using Wire Scanners (WS). The results are presented in this report and compared to simulations. The effect of the Coulomb scattering of the wire to the beam distribution is also addressed.

INTRODUCTION

Following the implementation of the LHC Injectors Upgrade (LIU) project [1], the Proton Synchrotron Booster (PSB) delivered beams that were well within the project's requirements. The optimization of the resonance compensation schemes and tune evolution along with the beta-beating compensation contributed to an increased beam brightness [2, 3], going beyond the initial predictions.

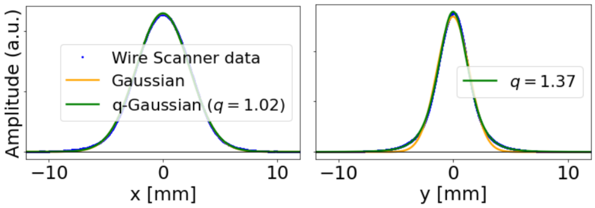

Figure 1: Ring 3 horizontal (left) and vertical (right) beam profiles of an LHC25-type beam close to extraction (t = 770 ms) in blue, Gaussian and q-Gaussian fits in orange and green respectively.

Measurements of the transverse beam profiles using Wire Scanners (WS) [4], revealed that the high-brightness beams have tails that differ from the ones of a normal distribution. These tails appear to be mostly in the vertical plane. Figure 1 shows an example of the transverse profiles close to extraction of the PSB Ring 3 for a bunch population of $N_b \approx 270 \cdot 10^{10}$ protons. The tails in the vertical plane are overpopulated. In order to investigate the possible sources of beam tail enhancement and to eventually improve the quality of the delivered beams, a measurement campaign was initiated. Beam profiles were acquired for different beam intensities, working points and energies during the acceleration cycle. This report summarizes the main results of these measurements focusing on the PSB ring 3. The measurements in the other PSB rings are similar.

FITTING NON-GAUSSIAN PROFILES

To characterize bunch profiles that follow a non-Gaussian shape, the q-Gaussian function [5] was used. The q-Gaussian is a generalized Gaussian function that incorporates a parameter q to model the weight of the distribution's tails. For $q = 1$, the q-Gaussian distribution coincides with a Gaussian distribution, for $1 < q < 3$ the distribution's tails are overpopulated, while if $q < 1$ the tails are underpopulated. The q-Gaussian function has been used in the past to model non-Gaussian beam profiles in the LHC [6]. The q-factor will be used throughout this report as an observable for the beam tail population.

BEAM TAILS AT INJECTION

Non-Gaussian beam tails are observed already at injection energies of the PSB. A typical vertical beam profile close to injection, for a low bunch population of $N_b \approx 10 \cdot 10^{10}$ protons, is shown in Fig. 2. The working point of this measurement is set to $(Q_x, Q_y) = (4.17, 4.23)$, which is a resonance free region. The beam tails are overpopulated ($q = 1.5$) but the tail population is not symmetric with respect to the beam core. At low beam energies, heavier tails are observed on one side of the profile compared to the other. This effect has been seen in previous studies [7], which suggest that the main contributor for this is the measuring instrument itself. In this study, an attempt to quantify and remove the undesired effects that the WS causes to the beam profile is made.

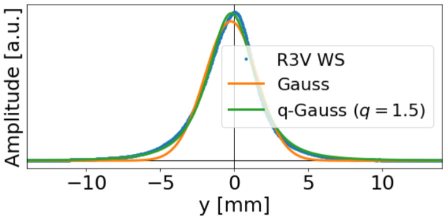

Figure 2: Ring 3 vertical beam profile of an LHC25-type beam close to injection (t = 290 ms) in blue, Gaussian and q-Gaussian fits in orange and green respectively.

---

* tirsi.prebibaj@cern.ch

Scattering on the Wire of the Instrument

In order to study the effects of the WS on the beam, a model that simulates the wire scan was implemented. In this model, an initial particle distribution is tracked using a one-turn map of the PSB. Turn after turn, a simulated moving wire is transversely displaced with a certain speed. At each turn, the particles that are intercepting with the moving wire are scattered with a certain angle distribution because of the Coulomb scattering. The free parameters of this model, the wire speed and width and the RMS scattering angle, have been calibrated using real WS profile measurements [8]. At injection energy of the PSB, the wire scan takes more than 3000 turns to be performed.

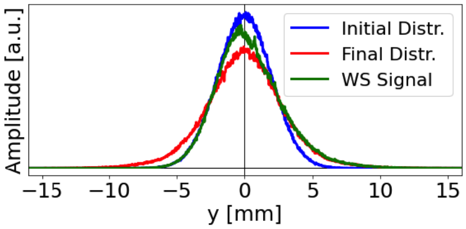

Figure 3: Asymmetric WS signal from wirescan simulations.

The interaction between the beam particles and the wire causes an increase in the beam size. Figure 3 shows a simulation of the beam size growth due to the wire scan. The particle distribution before the wire scan (initial) is shown in blue and the particle distribution after the wire scan (final) is shown in red. The signal recorded by the WS is proportional to the number of beam particles that the wire interacted with at each turn, as shown in Fig. 3 (green). Here, the scan is performed from left to right. For the first few hundreds of turns, the WS signal coincides with the initial distribution. While the scan advances, more particles are being scattered by the wire, and the beam size gradually increases. Towards the end of the scan, the beam size has already grown and so the WS signal coincides with the final grown distribution. For this reason, the recorded profiles appear to be asymmetric.

Figure 4 shows that the emittance increase $\delta\epsilon$ induced by the WS is independent of the emittance of the initial distribution. But, the low emittance profiles will appear more asymmetric since the relative growth in the profile is larger. $\delta\epsilon$ is also independent of the shape of the initial distribution as it follows a similar trend even if the initial distribution has overpopulated tails of $q \approx 1.5$ (orange line). Finally, for all cases the beam tails were not enhanced by the WS, meaning that particle distributions that already had tails before the wire scan, had similar or even less tails after the wire scan as well. The results from this simulation model are in a good agreement with the profile measurements [8] and with the analytical predictions for the emittance increase [9], but valid only for the injection energy of the PSB at 160 MeV. At higher energies the WS scattering effects are expected to be smaller [9], but the exact energy at which these become negligible needs further investigation.

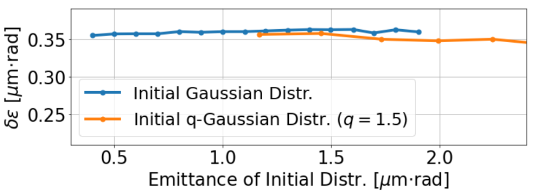

Figure 4: Emittance increase due to the WS scattering for an initial Gaussian (blue) and q-Gaussian (orange) distribution. Result from simulations.

This analysis allowed the removal of the profile growth and asymmetries induced by the WS from the measurement of Fig. 2. This was done by iteratively finding an initial distribution which, when performing the wire scan using the simulation model, gives a WS signal identical to this measured profile. This initial distribution is symmetric, has a smaller RMS beam size and constitutes an improved reconstruction of the real particle distribution in the PSB. It is plotted in Fig. 5 in green and it has tails that are still overpopulated ($q = 1.5$). Although the asymmetry of the tails is explained by the WS scattering, the tails themselves are not yet justified.

Comparison with the Linac4 Distribution

Thanks to the available profile monitors in the Linac4 [10] transfer line, a realistic particle distribution could be reconstructed [11] and used in simulation studies. Such a reconstructed particle distribution was tracked using PyORBIT [12] for approximately 15 thousand turns in the PSB lattice model (corresponding to the period from injection at $t = 275$ ms to $t = 290$ ms of the PSB operational cycle), including space charge effects. The resulting vertical profile is shown in Fig. 5 in purple. In the same Figure, this profile is compared with the measured distribution in the PSB, after removing the undesired WS effects as described in the previous section. It can be observed that the two profiles have almost identical tails ($q \approx 1.5$). This suggests that the vertical tails observed close to injection, for a low beam intensity and resonance free working point, are mainly due to the injected distribution from Linac4.

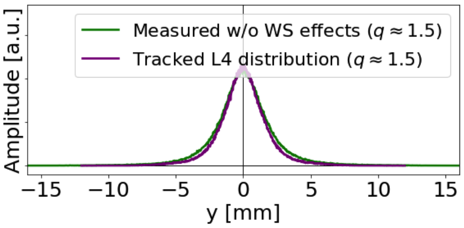

Figure 5: Comparison between Linac4 profile (purple) and PSB measured profile at $t = 290$ ms without the WS effects (green).

INTENSITY AND WORKING POINT

The vertical beam profiles change when the intensity increases. Figure 6 shows how the q-factor of the vertical beam tails at injection decreases as the beam intensity increases, for the working point of $(Q_x, Q_y) = (4.17, 4.23)$. The acquired profiles have been averaged over five shots and the errorbars represent the standard deviation of the applied q-Gaussian fits. While the intensity increases, the tune spread induced by space charge becomes stronger, as the beam has initially the same transverse emittance at injection. Thus, low action particles that have the strongest space charge detuning, hit resonances at integer tune $Q_y = 4$ causing an emittance growth (red points). Large amplitude particles do not interact with these resonances, leaving therefore the beam tails unchanged. Overall, the beam tails appear to become smaller (q-factor decreases) because the beam profile is dominated by the increased emittance of the beam core.

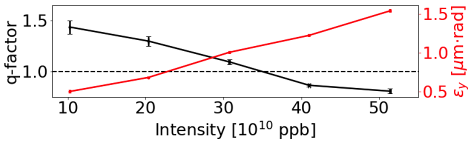

Figure 6: q-factor (black) and normalized emittance (red) of the vertical beam profiles as a function of beam intensity.

Resonances and space charge are closely linked with the beam tails. In fact, space charge induced periodic resonance crossing can result in losses, emittance growth or enhancement of the beam tails [13]. In the PSB, resonances up to fourth order are observed [3]. Although a global resonance compensation scheme has been developed through experimental and analytical studies [3], it is not possible to perfectly compensate all the resonances simultaneously.

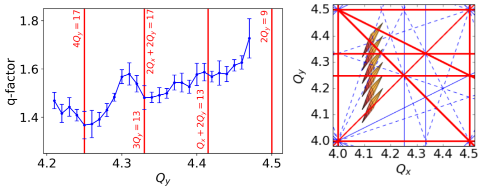

Figure 7: q-factor of the vertical profiles near injection as a function of the vertical tune (left) and tune diagram (right).

Figure 7 shows how the tails change when injecting at different working points. Here, the beam intensity is fixed at $N_b \approx 20 \cdot 10^{10}$ ppb, as well as the horizontal tune at $Q_x = 4.17$. The tune diagram on the right, shows some of the observed resonances in the PSB, highlighted in red. An analytical estimation of the space charge tune spread, for the beam parameters used, was calculated using PySCRDT [14] and plotted at some of the different injected vertical tunes. The left plot shows the dependence of the q-factor of the vertical profiles with respect to the vertical tune. For higher working points, the tails generally become stronger with the q-factor ranging between 1.3 and 1.7. A possible explanation for this is that for higher vertical tunes the beam may interact with multiple resonances at the same time.

BEAM TAILS ALONG THE CYCLE

In operational conditions, the high-brightness beams are injected in the PSB at the working point of $(Q_x, Q_y) = (4.40, 4.45)$ in order to mitigate the beam degradation from the strong space charge effects at injection energy. While the beam is accelerated and the space charge tune shift decreases, the tunes are dynamically changed towards the extraction working point $(Q_x, Q_y) = (4.17, 4.23)$ (top part of Fig. 8). The different resonances are crossed at different times and energies, which adds more complexity to the dynamics.

The result of all these mechanisms combined is shown in the bottom part of Fig. 8 . The q-factor of the vertical profiles is plotted throughout the PSB cycle for two different intensities. For $N_b \approx 270 \cdot 10^{10}$ppb the tails are enhanced throughout the cycle. For lower intensities ($N_b \approx 85 \cdot 10^{10}$ppb) the tails remain almost unchanged. The reasons for the difference in the evolution of the vertical tails for the different intensities is not yet clear and further measurements and studies are ongoing.

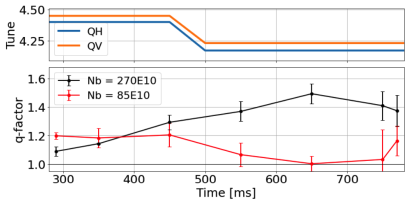

Figure 8: Tunes (top) and q-factor of the measured vertical profile (bottom) along the PSB cycle for two intensities.

SUMMARY AND OUTLOOK

In this paper, the vertical tails of the beams in the PSB were studied for different beam and machine conditions. At injection energies, the effect of the Coulomb scattering on the beam profile due to the wire scan were characterized and removed. For very low intensities, the observed tails were attributed to the already non-Gaussian distribution from Linac4. For higher intensities it was shown that the resonances in combination with space charge dominate the behavior of the tails in the PSB in a complicated manner.

Means for reducing the tail population and optimizing the beam accumulation are under development. Furthermore, the horizontal beam profiles must be addressed as well. Although they appear without tails, they are the result of the convolution with the momentum distribution as the instrument is installed in a non-zero dispersion location. The characterization of the horizontal beam tails requires deconvolution algorithms.

ACKNOWLEDGEMENTS

The authors would like to thank S. Albright, J.-B. Lallement, E.H. Maclean, B. Mikulec, F. Roncarolo and the PSB Operations team for the useful intputs and the continuous support.

REFERENCES

[1] J. Coupard (ed.) *et al.*, “LHC Injectors Upgrade, Technical Design Report, Vol. I: Protons”, *CERN-ACC-2014-0337* CERN, Geneva, 2014.

[2] 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 (HB2021)*, Fermilab, Batavia, Illinois, USA, Oct. 2021, paper MOP18, pp. 112-117. `doi:10.18429/JACoW-HB2021-MOP18`

[3] 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 (HB2021)*, Fermilab, Batavia, Illinois, USA, Oct. 2021, paper MOP06, pp. 40-45. `doi:10.18429/JACoW-HB2021-MOP06`

[4] 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`

[5] E. M. F. Curado and C. Tsallis, “Generalized statistical mechanics: connection with thermodynamics”, in *J. Phys. A25*, 1019 (1992).

[6] S. Papadopoulou *et al.*, “Impact of non-Gaussian beam profiles in the performance of hadron colliders”, in *Phys. Rev. Accel. Beams 23 10*, Oct. 2020 pp. 101004. `doi:10.1103/PhysRevAccelBeams.23.101004`

[7] A. Santamaría García *et al.*, “Study of the transverse emittance blow-up along the Proton Synchrotron Booster cycle during wire scanner operation”in *Proc. 10th Int. Particle Accelerator Conf. (IPAC’19)*, Melbourne, Australia, May 2019, pp. 1110–1113. `doi:10.18429/JACoW-IPAC2019-MOPTS101`

[8] T. Prebibaj *et al.*, “Wire Scan Impact on the Beam Profile for the PSB”, presentation at the Space Charge Working Group Meeting, CERN, Geneva, Switzerland, Oct. 2021. `https://indico.cern.ch/event/1088187/#4-aob-wire-scan-impact-on-the`

[9] F. Roncarolo, “Accuracy of the Transverse Emittance Measurements of the CERN Large Hadron Collider”, Ph.D. thesis, École polytechnique fédérale de Lausanne, Lausanne, Switzerland, 2005, pp. 70.

[10] L. Arnaudon *et al.*, “Linac4 Technical Design Report”, *CERN-AB-2006-084, CARE-Note-2006-022HIPPI*, CERN, Geneva, 2006.

[11] J.-B. Lallement *et al.*, “Linac4 to PS Booster optics matching”, presentation at the Injectors Performance Panel meeting nr. 7, CERN, Geneva, Switzerland, Apr. 2021. `https://indico.cern.ch/event/906075/contributions/3812020/attachments/2020869/3378963/L4_to_PSB_Matching-IPP.pdf`

[12] A. Shishlo, S. Cousineau, J. Holmes and T. Gorlov, “The Particle Accelerator Simulation Code PyORBIT”, *Procedia Computer Science vol. 51*, 2015, pp. 1272–1281. `https://www.sciencedirect.com/science/article/pii/S1877050915011205` `doi:10.1016/j.procs.2015.05.312`

[13] G. Franchetti and I. Hofmann, “Particle Trapping by Nonlinear Resonances and Space Charge”, in *Nucl. Instr. and Meth. A 561*, 2006, pp. 195-202. `doi:10.1016/j.nima.2006.01.031`

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