Summer Student Project Report

CERN SY-RF-BR

Longitudinal dynamics of the Barrier Bucket Multi-Turn Extraction transfer from PS to SPS

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Abstract

Barrier buckets are now running in operation since 2022 to limit beam loss at PS extraction for the SFTPRO beam, which is sent to the SPS North Area. Together with the Multi-Turn Extraction (MTE) scheme, these manipulations lead to particular transverse and longitudinal dynamics during the transfer process which require studies to increase the beam intensity. In this context, several beam tests on a copy of the operational SFTPRO beam were done during the internship in order to optimize the transfer process for intensities beyond operational values. In this report, a study of the longitudinal transfer dynamics of the SFTPRO beam is presented, along with intensity-dependant effects.

12/06/2023 - 25/08/2023

Contents

1 Introduction

In order to improve event rate and sharing of beams for future fixed-target experiments, the overall beam intensity has to be increased. Experiments in North Area require proton beams, served through the so-called proton chain highlighted in **Fig. 1**.

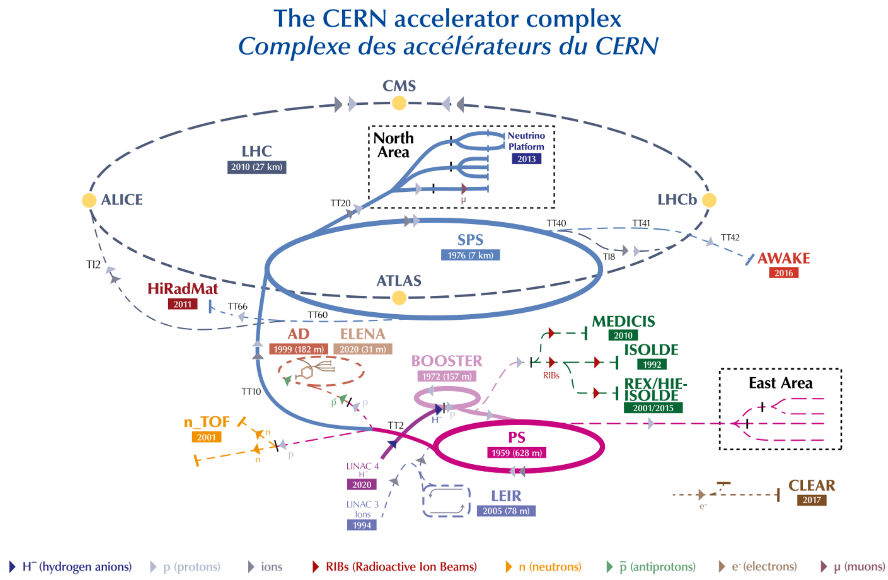

Figure 1: The CERN Accelerator Complex as of 2022. The original picture [1] was modified to highlight the parts relevant for the fixed-target beam studied throughout this studentship (in plain and thick lines). Copyright CERN.

For this particular type of beam, intensity is presently limited by beam loss, mostly during the transfer from the Proton Synchrotron (PS) to the Super Proton Synchrotron (SPS). Two methods were developed in order to minimize the losses :

- The Multi-Turn Extraction (MTE), which uses nonlinear magnets (sextupoles and octopoles) to split the beam in the transverse plane in four identical islands and a core by crossing a betatron resonance [2]. As the extraction starts, each island is transferred one turn after the other. It is worth noting that the first four islands are extracted sequentially due to the corkscrew shape of the beam. The extraction of the core requires the action of an additional transverse kicker. Since the SPS is 11 times longer than the PS, two full MTE cycles in the PS are required to (almost) fill the SPS.

- The Barrier Buckets (BB), a longitudinal RF manipulation also designed to minimize losses during the extraction process. Transfer from the PS to the TT2 line indeed requires using kicker magnets to deflect the beam towards the transfer line. However, the field generated by these magnets needs time to rise and if particles traverse the kickers during this rise time, they are not deflected correctly and end up being lost. By inverting the RF voltage of a single RF pulse in the time domain, one can create a flat bucket delimited by potential barriers in-between which particles drift freely and get reflected when reaching its borders [3], the so-called barrier bucket (see **Fig. 2** for a comparison with a conventional RF amplitude). No particles are supposed to reach the gap generated by the potential barriers, and hence beam loss can be removed if the barriers size and phase match the kicker rise time.

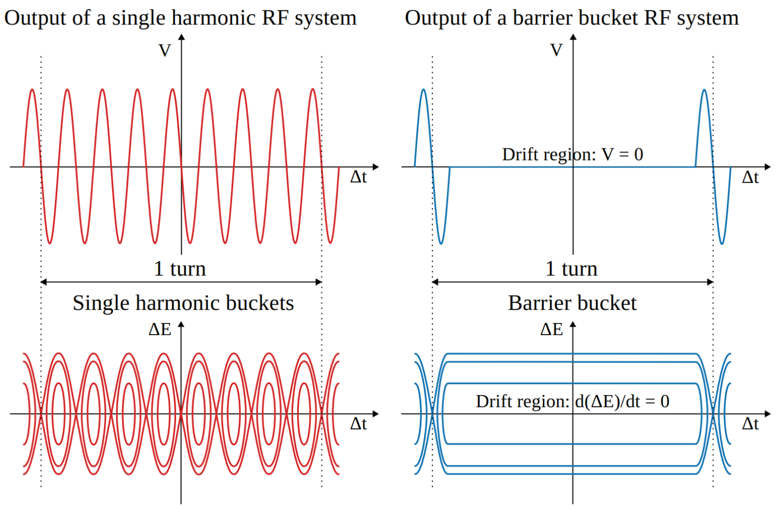

Figure 2: Comparison between conventional RF waveform (top left) and barrier bucket waveform (top right), with their corresponding longitudinal phase space (bottom). Figure from [4].

As these processes act on different planes (respectively transverse and longitudinal), they are supposedly independent and therefore are combined since 2022, showing remarkable results in terms of loss reduction up to moderate beam intensities [4]. The method is now even part of the routine manipulations of the operational SFTPRO cycle for the North Area.
The dynamics of such a combination however have not yet been studied deeply throughout the whole transfer process, and it has to be considered in order to increase the intensity to higher values. As this CERN Summer Studentship has been realized as part of the SY-RF-BR section focusing on longitudinal beam dynamics, this report will concentrate on the longitudinal aspects of the barrier bucket multi-turn extraction.

2 Beam tests and longitudinal dynamics

2.1 Data acquisition equipment and post-processing methods

2.1.1 Measuring longitudinal beam profiles

For the purpose of analysing longitudinal beam behaviour during the extraction from the PS and the injection to the SPS, the longitudinal line density has to be measured at relevant moments. For this reason, the beam profile before and during extraction from the PS was acquired by a Wall Current Monitor (WCM) measuring the image current induced by the passing beam and converting it into a voltage, proportional to the instantaneous beam intensity. In the TT2 transfer line, such measurements are then possible using a Wide-Band Pickup (WBP), again measuring the beam induced voltage in the capacitive device and delivering a voltage also proportional to the beam current. The longitudinal profile in the SPS was again measured with a WCM. The whole measurement setup is represented in **Fig. 3**.

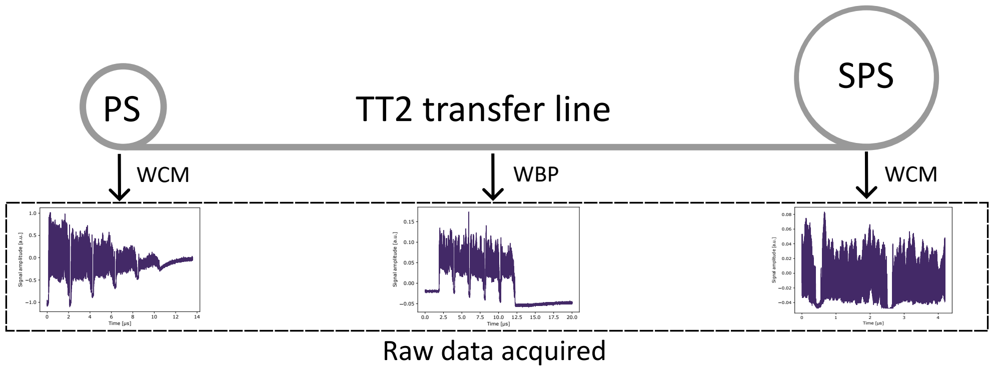

Figure 3: Schematic representation of the measurement setup in PS, TT2 line and SPS (not to scale), with corresponding measurement examples.

2.1.2 Post-processing methods

Analysing the PS and TT2 transfer line profiles requires to process data from two different instruments such that they can be compared. The very first step was to correct the baseline of both signals in order to compensate for the lower cut-off frequency of the pick-ups. Indeed, due to this high-pass behaviour, the average measured voltage is always equal to zero, which hides the fact that the line density in the gaps of the barrier bucket and after extraction must vanish. Based on these physical arguments, one can fit and remove the baseline of both raw signals to reconstruct the information lost by the low cut-off frequency of the pick-ups. One obtains signals on which the trace is at zero before injection, after extraction and in the gaps due to the barrier bucket. An example of such a baseline correction is shown in **Fig. 4**.

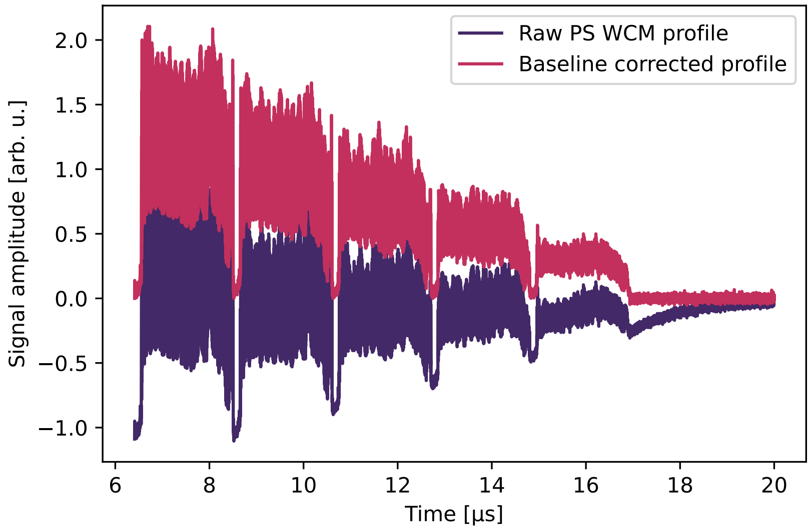

Figure 4: Examples of raw and baseline corrected PS WCM profiles during extraction.

As the TT2 signal corresponds to the beam profile after extraction, the longitudinal density is composed of the five islands (with a duration of almost one PS turn each) that were generated by the MTE in the transverse plane in the PS. By summing the signals from these five islands, one can reconstruct the original beam signal from the PS acquired few turns before the extraction.
A very important part of the post-processing treatment was to carefully separate these islands such that the reconstructed signal is similar and aligned with the signal from the PS WCM. This separation was possible by cross-correlating the WCM and WBP baseline-corrected signals to find the correct time at which the first island is extracted, corresponding to the time lag of the first peak on the correlation profile. All islands having the exact duration of one PS revolution period (approximately 2.10 µs), they were separated according to this time length.
Finally, both signals were normalized to compensate for the sensitivity differences between the WCM and WBP. The results obtained with these post-processing techniques are presented in **Sec. 2.2.1**.

2.2 Longitudinal beam dynamics throughout the transfer process

The initial goal of this project being to optimize the barrier bucket multi-turn extraction for high intensity beams, the results shown in this section will deal with the highest intensity for which data has been acquired, in this case $3.0 \cdot 10^{13}$ protons per pulse. Intensity studies, and especially with an even higher intensity of $3.3 \cdot 10^{13}$ protons per pulse are shown in **Sec. 2.3**.

2.2.1 Between the PS and TT2 transfer line

An initial study was to compare the beam in the PS profile during one turn before the start of the extraction with the sum of the islands in the TT2, as explained in **Sec. 2.1.2**. The profile comparison after post-processing, normalization and time alignment is shown in **Fig. 5**. Qualitatively, both profiles seem very similar, with the exception of their width, which is smaller in the TT2 sum profile. Such differences can be explained by differences in the digitizer bandwidth between the PS WCM and the TT2 transfer line WBP.

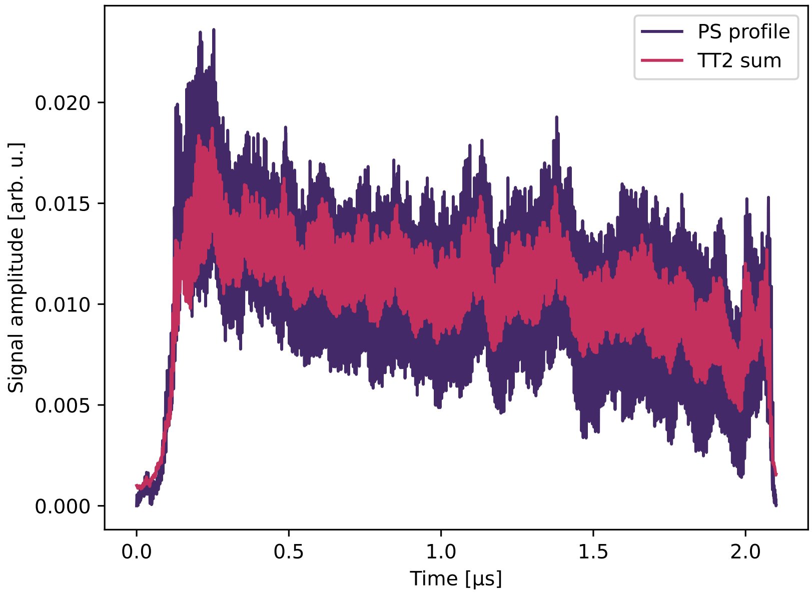

Figure 5: Longitudinal beam profile in the PS for one turn before the start of the extraction, together with the reconstructed profile from the summed TT2 five islands.

A quantitative comparison of these profiles can be done through cross correlation, as illustrated in **Fig. 6.a**. The normalized correlation shows a very high peak at 0.9856, which demonstrates the profiles are almost identical. Fast variations in the cross correlation profile can be seen around the peak, but a zoom on this region as in **Fig. 6.b** shows well-defined sinusoidal oscillations with a period of 5 ns.

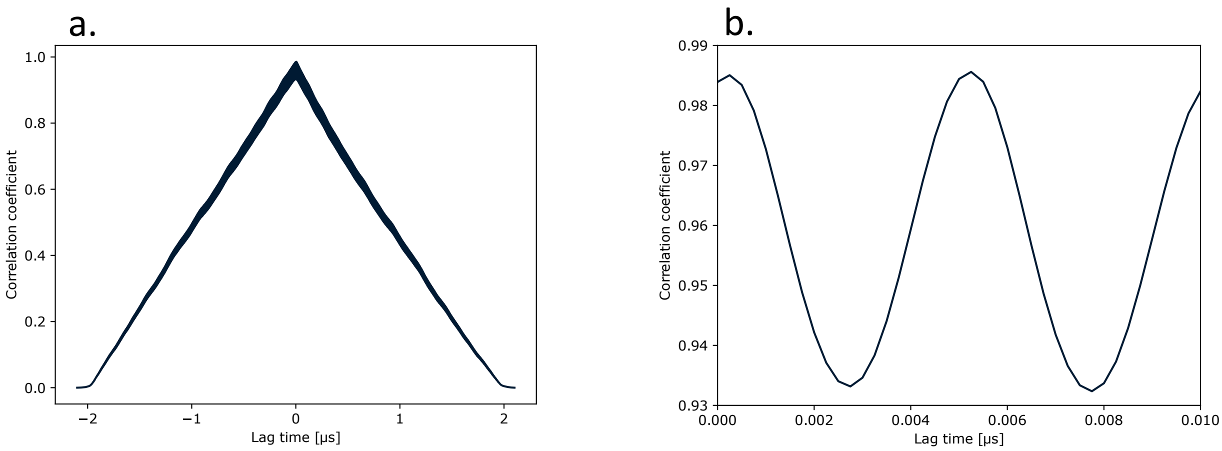

Figure 6: Cross correlation between the two signals. **a.** Normalized cross correlation, showing a triangular shape envelope similar to a square signal auto-correlation, peaking at 0.9856. **b.** Zoom on the peak region, revealing fast and well-defined variations of period of 5 ns, corresponding to the 200 MHz modulation.

This type of oscillations is not surprising as a 200 MHz modulation (corresponding to periods of 5 ns) is applied in order to prepare the bunches for their injection into the SPS. As this modulation is present in both the PS and TT2 profiles, the variations seen in the correlation profile are the result of small time shifts caused by the cross correlation combined with very fast oscillations due to the 200 MHz modulation. The nature of these differences is hence purely due to the correlation and does not indicate dissimilarities in the profiles throughout the extraction process, and therefore no particular longitudinal extraction dynamics. The 200 MHz modulation actually allows to precisely align the WCM signal in the PS and the WBP data from the TT2 transfer line to the sub-nanosecond level.

2.2.2 Injection in SPS

Measurements at the SPS have been performed for the first thousand turns after injection using the operational SFTPRO beam with an intensity of about $1.2 \cdot 10^{13}$ protons per pulse. The time evolution of the longitudinal profile of different bunches (of a same cycle) as seen in **Fig. 7** indicates differences in the bunch distributions, but similar types of longitudinal oscillations.

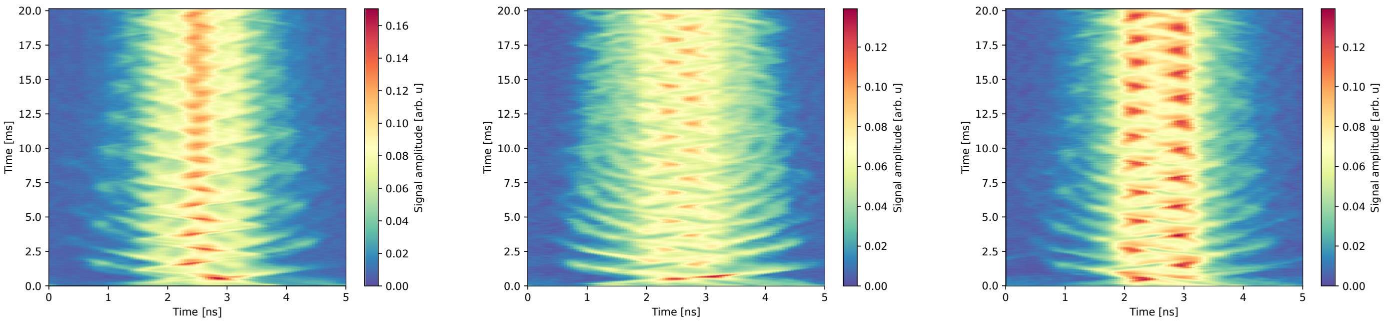

Figure 7: Evolution over time (vertical axis, around 10^3 SPS turns) of the longitudinal profile (horizontal axis) of three different bunches in the SPS, performing dipole and quadrupole oscillations. Clear quadrupole (length) oscillations can be observed on the left profile, and dipole (position) oscillations on the right profile from the beginning to the end. All profiles however undergo a combination of both types of oscillations.

Firstly, the longitudinal profiles of the bunches seems to alternate between a more peaked, intense profile and a flatter distribution. This type of behaviour is identified as quadrupole oscillations, due to the rotation of a stretched bunch in the longitudinal phase space. These coherent oscillations eventually decrease due to filamentation. Another type of oscillations cause the bunch to oscillate in phase around the center of the bucket. Such dipole oscillations occur due to a mismatch of the injected bunch in phase and/or energy in the longitudinal phase space. The bunches are therefore likely injected with small phase and/or energy errors, as well as into buckets with unmatched RF voltages, the latter triggering the observed quadrupole oscillations. The bunches themselves are different from one another and tend to indicate they were not uniformly shaped during the 200 MHz modulation in the PS.

2.3 Intensity effects

2.3.1 Longitudinal instabilities at intermediate plateau and on the flat-top

Additional beam tests were done towards the end of the project to increase the beam intensity as far as possible, in order to determine where instabilities or beam loss would start appearing. At an intensity of $3.3 \cdot 10^{13}$ protons per pulse, longitudinal instabilities appear at the intermediate plateau as illustrated in **Fig. 8.a**, just before the $h = 8$ to $h = 16$ longitudinal beam splitting. The instabilities interestingly stop after the splitting. The instability might disappear due to different scalings with bunch intensity and bunch length versus RF voltage (80 kV on $h = 8$ and 120 kV on $h = 16$), but no quantitative study has be performed to confirm this hypothesis. A proper coupled-bunch feedback can be however set up to damp the oscillations for the $h = 8$ and hence mitigate the instability.
The beam profile on the flat-top indicates no particular sign of longitudinal instability during the transverse splitting and debunching process, as illustrated in **Fig. 8.b**. The absence of instabilities during debunching is an important information as the barrier bucket synchronisation process afterwards excludes the application of conventional beam control loops and feedback systems to remove them.

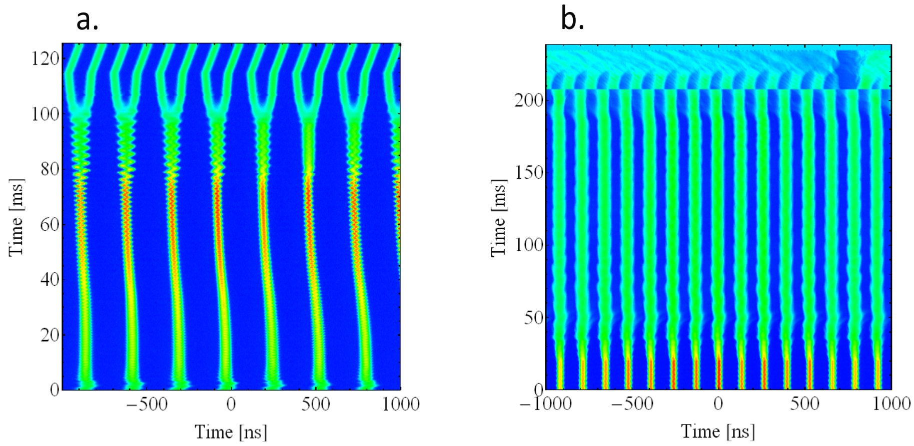

Figure 8: a. Longitudinal beam profile from injection to the intermediate plateau, showing the growth of instabilities before the $h = 8$ to $h = 16$ splitting. **b.** Longitudinal beam profile at the flat-top, during the debunching process and the transverse splitting at low RF voltage, showing no relevant sign of instabilities. The glitch at 210 ms appears due to a switching of the trigger signals, just before the handover from the conventional to the barrier bucket.

2.3.2 Deformation of the beam profile versus intensity

As intensity increases, the longitudinal bunch profile (both in the PS and in the TT2 transfer line) seems to undergo some deformation that introduces an intensity-dependant gradient of the profile, as shown in **Fig. 9**. This effect is due to the shape of the barrier bucket, that is not exactly flat and symmetric anymore due to the significant beam-induced voltage in the broadband cavity.

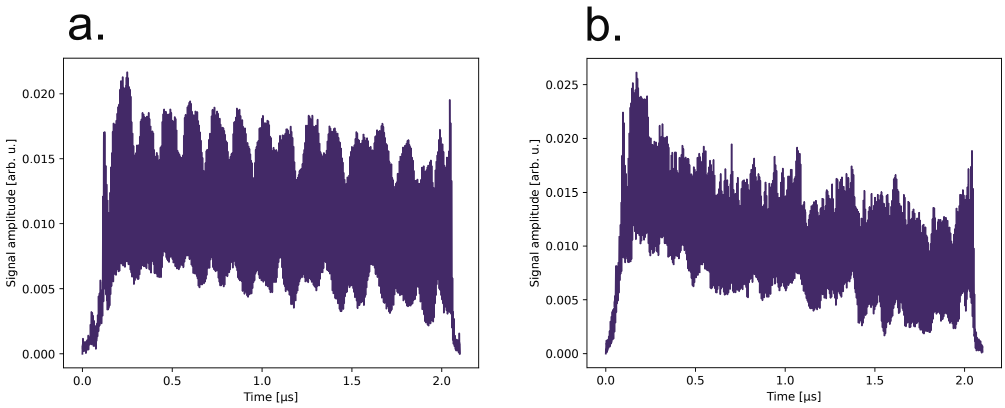

Figure 9: Single-turn longitudinal profile in the PS for two different intensities. **a.** $N = 1.2 \cdot 10^{13}$ protons per pulse. **b.** $N = 3.0 \cdot 10^{13}$ protons per pulse.

By linearly fitting the beam profile (excluding the barrier gaps) and extracting the slope of this fit for all data-sets acquired at each intensity, one can determine how these slopes evolve with increasing intensity. **Figure 10** reveals a decreasing behavior with intensity. Considering that the beam-induced voltage is proportional to the beam intensity, a linear fit was a reasonable first-order choice that might give enough information to optimize the pre-distortion of the drive voltage to the wideband cavity so the profile gets straightened up for future high-intensity operation.

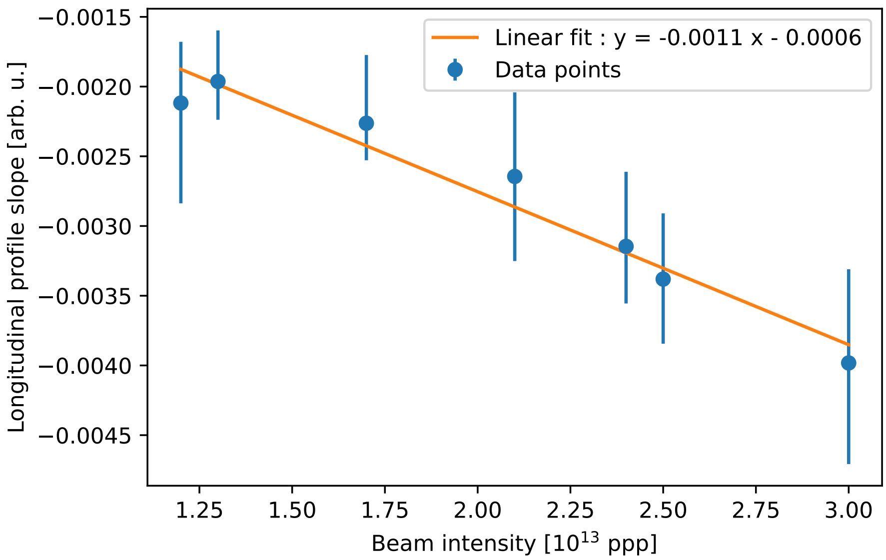

Figure 10: Linear fit illustrating the proportional dependence of the mean bunch profile slope versus intensity.

3 Conclusions and perspectives

This summer student project consisted in a detailed study of the longitudinal dynamics of barrier bucket multi-turn extraction transfer from the PS to the SPS for high intensity beams. As expected, the beam profiles measured before extraction from the PS agree very well with the sum of the five turns observed in the TT2 transfer line, revealing no particular longitudinal issues during the extraction process. At injection into the SPS, dipolar and quadrupolar bunch oscillations can be observed, likely due to small phase and/or energy mismatches and unmatched RF voltages at injection. These oscillations reveal that the bunch profiles must be adjusted thoroughly during the 200 MHz modulation since they will define the longitudinal parameters for the rest of the SPS cycle and contribute to losses downstream. High intensity studies showed the emergence of longitudinal instabilities at the intermediate plateau, before the $h = 8$ to $h = 16$ longitudinal beam splitting, that however are removed by the splitting. Fortunately, on the flat-top, the debunching process and transverse splitting process at low RF voltage does not trigger instabilities, indicating that the beam intensity might be pushed farther. As intensity increases, the bunch profile slope also gets larger but RF drive adjustments for the barrier bucket cavity might be possible to flatten the profile and compensate for beam-induced voltage.

A next step would be to study turn-by-turn the island profiles in the TT2, as this report focused mostly on the sums of the islands and not the profiles. The islands are indeed different from each other, some having intensity peaks and others not. These differences are apparently compensated when the islands are added up, but reveal that the multi-turn splitting process does not distribute the longitudinal profile uniformly, ultimately pointing to coupled longitudinal-transverse beam dynamics.

Acknowledgements

This studentship was a pleasure, but it would have been much more harder without all the persons who contributed directly or indirectly to it. I would first like to thank my supervisors, Heiko Damerau and Alexandre Lasheen, for choosing me as their Summer Student and for all the help and mind-blowing explanations they gave me during this studentship. I also want to thank all the RF-BR section members for providing such a nice working environment, and especially Oleksandr Naumenko who helped me not only for the SPS measurements, but also for checking on me from time to time and answering my questions. I address special thanks to Mihaly Vadai, whose thesis strongly made the complex barrier buckets dynamics much more understandable, and who kindly discussed with me about technical topics during the section barbecue. I would also like to thank Helena Perovic, my desk mate, for all the conversations we had that enlightened my mind and kept me going forward for my project. Finally, thanks to all the friends I met here for the good moments and beautiful memories we made together.

References

[1] E. Lopienska. *The CERN Accelerator Complex*. 2022.

[2] A. Huschauer et al. "Transverse beam splitting made operational: Key features of the multiturn extraction at the CERN Proton Synchrotron", *Physical Review Accelerators and Beams* 20 (2017), p. 061101.

[3] M. Vadai. "Beam Loss Reduction by Barrier Buckets in the CERN Accelerator Complex". Dissertation. CERN, Geneva (Switzerland), 2021.

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4 Appendix - Summer Student Poster

Barrier bucket multi-turn extraction from PS to SPS for fixed-target experiments

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Introduction and motivation

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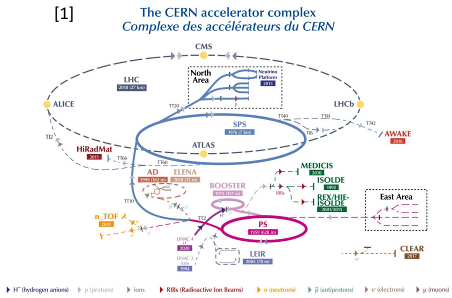


Fixed target experiments require large numbers of protons, but intensity is limited by **beam loss**, in particular during the **transfer from PS to SPS**.
Two processes were developped to minimize these losses :

- <u>Multi-turn extraction</u> (MTE) : Beam splitting in **5 islands in the transverse plane** using nonlinear magnets before **extracting one island per turn** [2].
As PS circumference is $^{1}/_{11}$ of SPS, MTE can almost **fill SPS in 2 PS cycles**.

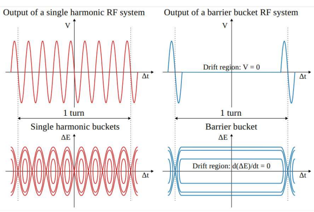
- <u>Barrier buckets</u> (BB) : The field in the kicker magnets aiming to deflect the beam towards the transfer line needs time to rise. If the beam passes through the kickers during this **rise time**, it will result in **beam loss**. **Longitudinal manipulations** (barrier buckets) were designed to generate a kicker gap and avoid this effect [3].

→ The combination of these two techniques is operational up to moderate intensities [4], but has yet to be optimized for **high intensity** both on the longitudinal and transverse plane.

Barrier bucket principle

In usual RF systems designed for acceleration, the electric potential is applied in the form of a **sine wave, at an integer multiple of the revolution frequency**, confining particles in **bunches** inside the so-called **RF buckets**.

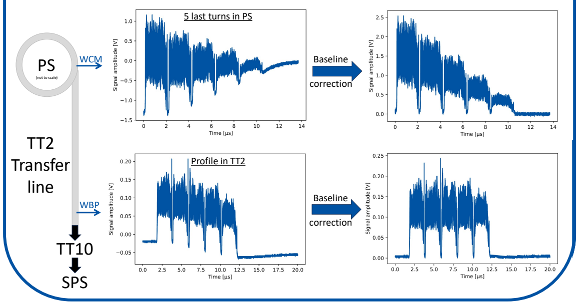
[4]



→ By inverting the RF voltage of a single pulse in the time domain, one can create a **flat bucket** (the **drift region**) delimited by **potential barriers**. If the **size** and **phase** of the potential barriers **match the ramping time**, no particles will traverse the kickers while they rise, **avoiding beam loss**.

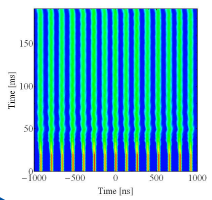
First Measurements

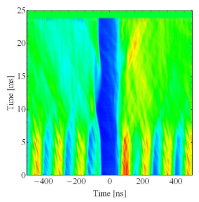
Measurements were done (05/07/2023) to study the **longitudinal bunch profile** in both PS and TT2 transfer line. **Baseline corrections** were applied during post-processing for data analysis purposes.



Intensity effects

At **high intensity**, **instabilities** tend to appear. In the case of usual RF systems, **control loops** act on the RF fields to prevent these instabilities from growing. However, the **barrier bucket synchronization** requires to **disable these loops** at the start of the flat-top. Hence **beam instabilities cannot be damped** with conventional techniques.
During last MD (19/07/2023), the beam intensity was **pushed up to $3{\cdot}10^{13}$ protons per pulse**, without relevant sign of longitudinal instability.





What to do next ?

→ The data acquired on 05/07/2023 and 19/07/2023 has **yet to be analysed in detail**. In particular, the **bunch profile in PS** can be compared **with the sum of each island in TT2**. In absence of losses during extraction, both profiles are supposed to be **strictly identical**. Different profiles (by taking losses into account) hence reveal the **particular dynamics of the five-turn extraction process**.

→ **Pushing beam intensity** as much as possible is the main objective for future fixed-target experiments. An intensity of **$3{\cdot}10^{13}$ is the highest studied so far**, but the absence of instabilities indicates that reaching even **higher intensities will be possible**. The next MDs will focus on carefully **increasing intensity** up to the **instability treshold**, while maintaining clean beams with minimal losses.

→ Future results will be reported on my CERN Summer Student Project Notes. Feel free to look at it if you're interested !

<u>References</u> :

[1] E. Lopienska, *The CERN Accelerator Complex* (original picture modified). Copyright CERN (2022)
[2] A. Huschauer et al, *Transverse beam splitting made operational: Key features of the multiturn extraction at the CERN Proton Synchrotron,* Phys. Rev. Accel. Beams **20** 061001 (2017)
[3] M. Vadai, *Beam Loss Reduction by Barrier Buckets in the CERN Accelerator Complex*, Thesis (2021)
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