LONGITUDINAL COLLECTIVE EFFECTS AT BEAM TRANSFER FROM PS TO SPS AT CERN

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Abstract

The hardware upgrades of the LHC Injectors Upgrade (LIU) project at CERN were completed during the Long Shutdown 2 (2019-2021) to prepare the injectors for the beams required by the High Luminosity (HL) LHC. Doubling the bunch intensity leads to new challenges due to collective effects. Although many bottlenecks were already solved, a remaining limitation is the important loss of particles at transfer from the Proton Synchrotron (PS) to the Super Proton Synchrotron (SPS). The maximum transmission achieved since the restart in 2021 is in the order of 90%, yet leading to unnecessary activation of the SPS. The losses are distributed at various instants of the SPS cycle: fast intensity decay right after injection, slow losses along the injection plateau while waiting for multiple injections from the PS, and uncaptured beam removed at start of acceleration. In this contribution, the focus is on longitudinal aspects of transfer losses and more specifically on intensity effects during the non-adiabatic bunch shorting performed in the PS prior to extraction, as well as on the longitudinal mismatch at injection due to misaligned bunch phases in the SPS caused by transient beam loading.

INTRODUCTION

The design and improvements of the transfer of LHC-type beams from the PS to the SPS is a long standing topic of study. The main challenge resides in transferring long bunches from the PS (with longitudinal emittance $\varepsilon_l = 0.35$ eVs), to the short RF buckets in the SPS. A non-adiabatic bunch shortening is performed in the PS by applying a fast voltage increase with two pairs of cavities at 40 MHz and 80 MHz [1, 2]. The corresponding RF voltage program as set in operations in 2023 is displayed in Fig. 1 (left). This process brings the bunch length from about $\tau_l = 4\sigma = 11$ ns to $\tau_l = 3.8$ ns, allowing the bunches to fit in the 5 ns SPS RF bucket (Fig. 1 middle, σ is the RMS bunch length). One drawback are longitudinal tails which do not rotate entirely due to the non-linearity of the RF bucket, and are then lost at capture in the SPS (Fig. 1, right).

Extensive studies were conducted in view of doubling the beam intensity for the High-Luminosity (HL) LHC [3]. These studies included beam measurements [4] and simulations to investigate potential for improvements (in the PS [5] and in the SPS [6–8]). Following the LHC Injector Upgrade project [9] completed in 2021, the best achieved transmission in 2022 was 90% with injection of multiple trains in the SPS [10] at the baseline intensity of $N_b = 2.6 \times 10^{11}$ protons per bunch (ppb) and 25 ns bunch spacing. From the present losses, about 20% are occurring at the start of acceleration and can be measured as longitudinally uncaptured beam. These appear to increase overproportionnally above $N_b = 2.0 \times 10^{11}$ ppb pointing towards collective effects. In this paper, we present advancements of the simulation on the PS side to better represent collective effects during the bunch rotation, as well as recent observations in the SPS measured at highest beam intensity.

TRANSIENT BEAM LOADING DURING BUNCH ROTATION IN THE PS

An important effort was invested to update the PS longitudinal impedance model to improve the treatment of RF systems with feedback loops [11]. To build this model, a thorough survey of all equipment in the ring was done, complemented by the representation of the impedance through RF measurements or simulations. The most important contributions are the RF systems (25 systems tuned at six different frequencies). Simulations using the BLonD tracking code [12]

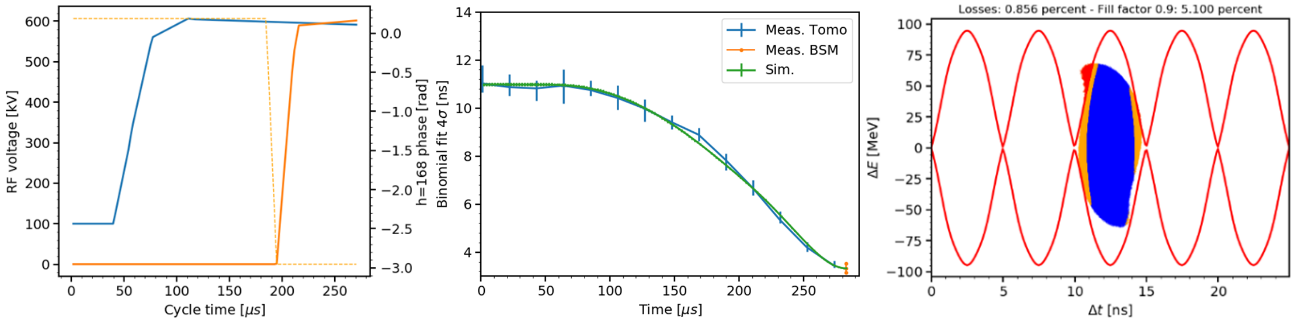

Figure 1: The RF voltage program during the bunch rotation before extraction of the LHC-type beams from the PS (left), the corresponding bunch length evolution (middle, measured and simulated), and the simulated longitudinal phase space distribution at extraction (right). The losses are evaluated in simulations by considering particles outside of the SPS RF bucket as lost (in red), as well as the particles too close to the separatrix (orange, 90% in amplitude from separatrix).

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including the latest impedance model could reproduce well the evolution of the bunch length during the bunch rotation as shown in Fig. 1 (middle) and were used to analyze the influence of the main impedance sources. All of them have a different impact on the bunch rotation depending on their effective impedance. In this paper, the focus is put on the contribution from the RF systems.

In the PS, the resistive impedance of the cavities at 40 MHz (main RF harmonic $h = 84$) and 80 MHz (second RF harmonic $h = 168$) cause transient beam loading as the ring is not completely filled with bunches. This changes the effective voltage and phase along the train leading to bunch-by-bunch variations of the centroid evolution as shown in Fig. 2 (left). Bunches start with a different synchronous phase shift, which will be translated into variable offsets in phase and in energy and after the bunch rotation. This offset with respect to the center of the SPS RF bucket leads to additional loss of tail population at the edges of the separatrix.

The effect can be mitigated using a Multi-Harmonic Feedback system (MHFB) which can reduce the impedance by a factor of 10 at the revolution frequency harmonics, except for the central harmonic when cavities are pulsing [13]. Although its original purpose is to reduce uncontrolled longitudinal emittance blow-up, present simulations reveal its potential benefits for PS-SPS transfer as the MHFB significantly reduces the bunch-by-bunch variations of the synchronous phase shift as shown in Fig. 2 (middle).

Simulations were then performed by optimizing the bunch rotation parameters (relative time and phase between 40 MHz and 80 MHz pulse and extraction time) to minimize losses in the SPS. The PS bunches are then centered in the SPS RF bucket (without intensity effects), preserving the relative bunch-by-bunch shifts in phase and energy due to the bunch rotation. This effectively simulates an ideal capture in the SPS with perfect loops. Moreover, the usage of a third 80 MHz cavity (presently kept as spare) as well as a linearization of the bunch rotation were considered [5, 14]. The linearization is obtained by applying a step in voltage with the 80 MHz RF system in bunch lengthening mode (between 50 µs and 200 µs on Fig. 1 (left) and the phase is then jumped back to bunch shortening mode). Regarding the input beam parameters, the tails of the longitudinal profile were varied for the same RMS bunch length to account for potential longitudinal halo generated during the accelerating cycle before the bunch rotation. Results of all cases are summarized in Fig. 3.

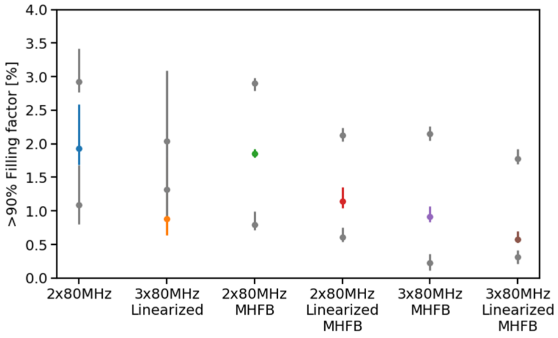

Figure 3: Best achievable losses in simulations at $N_b = 2.6 \times 10^{11}$ ppb for various bunch rotation schemes: linearized bunch rotation, third 80 MHz cavity enabled, with MHFB. The error bars correspond to bunch-by-bunch spread in losses along the train while the grey dots represents simulations with small (less losses) and large tails (more losses).

According to simulations, improvements in terms of losses can be obtained if the MHFB is enabled. In that configuration, and for cases where the longitudinal tails are not too large, losses can be reduced by a factor of 4 thanks to the improved shape of the extracted PS bunches with linearization or an extra RF system. However, the improvements predicted in simulations were not yet completely achieved with beam due to the operational complexity of the scheme. More beam observables are needed to better qualify tails and the effective relative phase between the RF systems, as well as a lengthy optimization process. Further collective effects are expected in the SPS at injection which are not included in simulations for the PS.

TRANSIENT BEAM LOADING INTO THE SPS INJECTION

In 2022, first observations of bunches injected in the SPS revealed important injection oscillations as illustrated in Fig. 4. The quadrupolar (or bunch length) oscillations at

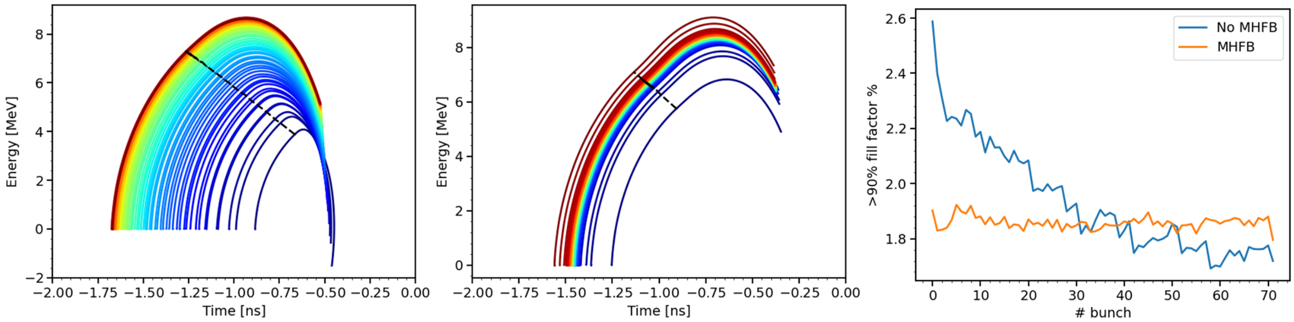

Figure 2: Bunch-by-bunch evolution of the centroid during bunch rotation without (left) and with (middle) the MHFB systems. The first bunches in the train are displayed in blue and the last in red. The dashed black line represents the moment when 80 MHz cavities are pulsing. The corresponding bunch-by-bunch losses as defined in Fig. 1 (right) are shown on the right.

injection are expected, and they are due to the mismatch of the rotated PS bunches with respect to the SPS RF buckets. Nonetheless, the more relevant observation was the increased dipolar (or bunch phase) oscillations for bunches at the extremities of the batch. This was associated with the increased uncaptured beam and losses above bunch intensities of $N_b = 2.0 \times 10^{11}$ ppb.

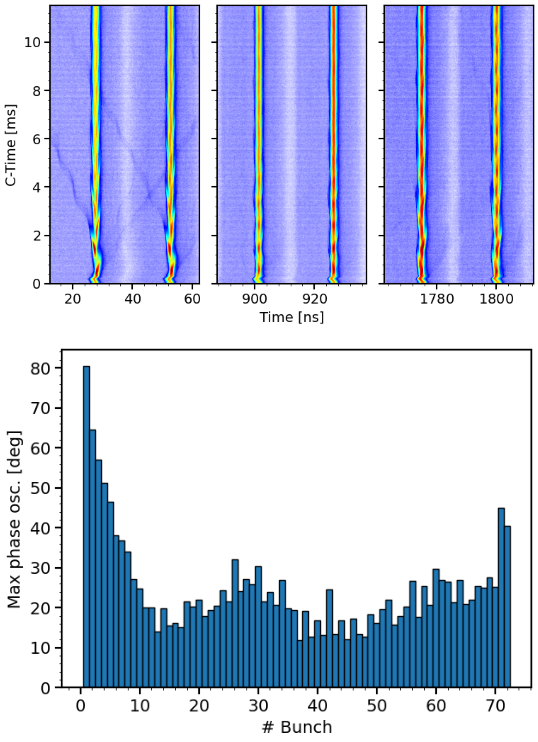

Figure 4: Injection oscillations in the SPS at $N_b = 2.6 \times 10^{11}$ ppb. Bunch evolutions is shown on top for the first two, middle two, last two bunches. Each line of the figure corresponds to a profile measured each turn which are then stacked vertically to observe oscillations and uncaptured beam. The bottom figure summarizes the maximum dipole phase oscillations (peak-peak) along the train.

A summary of the maximum phase oscillations as a function of the bunch intensity N_b is given in Fig. 5. The chosen criterion was to compare the maximum phase oscillations (from bunches in extremities, large transient beam loading) to the minimum (in the middle of the train, small transient), revealing a clear dependency of phase oscillations with the bunch intensity. A bunch-by-bunch shift in phase and in energy is expected from intensity effects in the PS as described above. Nonetheless, the shifts obtained in simulation are not sufficient to explain the values from Fig. 5. Indeed, a maximum of 10 degrees in the SPS RF buckets is expected from transient beam loading in the PS, or up to 10 MeV energy mismatch which corresponds to about 10 degrees in the SPS RF buckets after one quarter of the synchrotron period. Overall, a linear dependency of the transient beam loading with intensity is measured, but the corresponding losses appear to be non-linear and larger towards $N_b = 2.6 \times 10^{11}$ ppb.

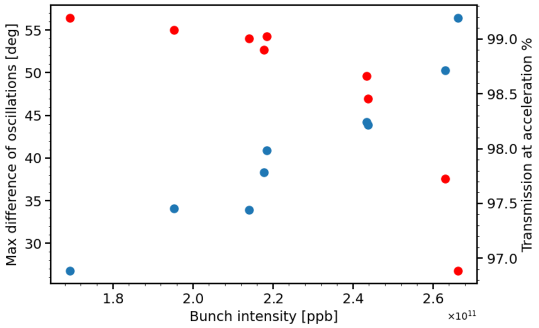

Figure 5: Difference between the largest and the smallest dipole phase oscillation amplitude along the train as obtained from Fig. 4 (blue) as a function of the bunch intensity N_b, together with the reduced transmission due to the uncaptured beam at start of acceleration (red).

A possible explanation for the measured phase oscillations is the transient beam loading in the SPS. Like in the PS, the uneven filling of the SPS results in a modulation of the effective RF voltage and phase experienced by each bunch. This effect is mitigated by the usage of a One Turn Delay FeedBack (OTDFB) systems [15]. Nonetheless, despite the obtained impedance reduction by a factor of 10, a residual phase shift of the RF buckets towards the start and the end of the batch remains, in the order of 15 degrees on both extremities of the batch, with opposite signs. The action of the OTDFB is rapid and takes in the order of a couple of SPS turns to reach full impedance reduction, yet small compared to the synchrotron period. At injection, the effective phase of the SPS RF bucket with respect of the incoming PS beam is then shifted along the batch and can cause phase oscillations. These cannot be reduced by the beam phase loop which averages the phase error over all bunches. Simulations coupling both PS and SPS are now under development to be compared with present measurements and fully understand the mismatch induced by transient beam loading at PS-SPS transfer [16].

CONCLUSIONS

Mismatches caused by transient beam loading at the bunch-to-bucket transfer from the PS to the SPS can cause losses due to uncaptured particles. In the PS, transient beam loading cause a bunch-by-bunch shift in phase and energy, which subsequently offsets bunches with respect to the SPS RF buckets. In addition to the already complicated bunch rotation scheme, this leads to push the longitudinal tails beyond the separatrix of the SPS RF buckets. Due to transient beam loading in the SPS, the receiving RF buckets are actually modulated in phase. The effective position of the SPS RF buckets are shifted along the batch, causing additional mismatch and uncaptured beam. Further studies are planned with the complete feedback systems in the SPS (Feed Forward [17], commissioned in 2023) and improved modeling in simulations [18] to fully reproduce the longitudinal mismatch at PS-SPS transfer.

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