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CAPTURE AND FLAT-BOTTOM LOSSES IN THE CERN SPS

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Abstract

Particle losses on the flat bottom of the SPS, the last accelerator in the injector chain of the LHC at CERN, are a strong limitation for reaching the high intensities required by the high-luminosity upgrade of the LHC. Two contributions to these losses are investigated in this paper. The first losses occur during the PS-to-SPS bunch-to-bucket transfer, since the bunch rotation in the PS creates halo particles and the bunch does not completely fit into the SPS RF-bucket. The effect of longitudinal shaving in the PS on the beam transmission was recently tested. At high intensities, further capture losses are caused by beam loading in the main travelling wave RF system of the SPS, which is partially compensated by the LLRF system, in particular by the one-turn delay feedback. While the feedforward system reduces the capture losses, it also increases the losses along the flat bottom due to the RF noise.

INTRODUCTION

The High Luminosity LHC (HL-LHC) project requires 2.3×10^{11} protons per bunch (ppb) at injection. For the SPS, the last accelerator in the injector chain, this requires an injected intensity of 2.6×10^{11} ppb to account for a loss budget of 10 % [1]. To achieve the HL-LHC goals, the LHC Injectors Upgrade (LIU) program aims at improving the performance of the entire LHC injector chain. The LIU target intensity is a challenging goal for the SPS, since it means a doubling of the present nominal LHC intensity of 1.15×10^{11} ppb. Major limitations are instabilities and intensity-dependent losses [2]. In this contribution, we focus on longitudinal losses in the SPS at injection and during the flat bottom. Instabilities further degrade the beam quality and can develop at flat bottom, during ramp or at flat top. Flat-bottom instabilities are discussed in [3], while instabilities during ramp and their mitigation were recently considered in [4].

CAPTURE LOSSES

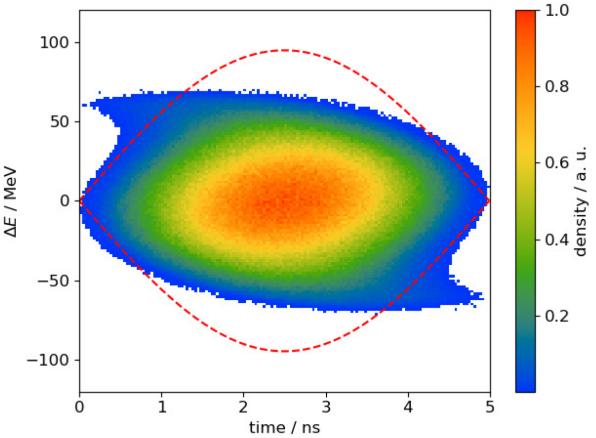

Figure 1: Simulated phase space density after PS bunch rotation. The red dashed line indicates the SPS RF-bucket. About 1 % of the particles are in a halo outside the RF bucket.

The PS is the injector of the SPS and its RF system operates at 40 MHz at extraction. However, the bunches with nominal emittance of 0.35 eVs would not fit into the RF bucket of the 200 MHz system of the SPS. To reduce their length, bunches are rotated in longitudinal phase space before extraction. Due to RF non-linearities, the rotated bunch has an ‘S’-shape [5], as shown for a simulated phase space density in Fig. 1. Even though the main part of the bunch with a length of 3.8 ns fits into the 5 ns RF bucket of the SPS (dashed line), the RF bucket is completely full after filamentation. Moreover, in the example of Fig. 1 about 1 % of the particles reside in a halo *outside* of the RF bucket and cannot be captured.

Measurement Technique

For capture loss estimation in the SPS, measuring the beam intensity by a Beam Current Transformer (BCT) is not sufficient. First, the resolution of the BCT is only 10 ms, which is not enough to describe the capture losses that occur during the first few milliseconds. Second, the uncaptured particles are present in the SPS till the start of the ramp and contribute to the BCT signal. Instead, we measure the intensity with a wall current monitor and a fast oscilloscope on a bunch-by-bunch basis by using the bunch profiles. The bunch intensity is obtained by integrating the bunch profile and calibrating against the BCT value at a time in the cycle when the uncaptured beam is removed, e.g. at the beginning of the ramp or after using a tune-kicker in the beam gap. A systematic error of this method can come from uncaptured beam that drifts in phase space either above or below the bucket, and, thus, contributes to the measured bunch intensity.

Measurements

One method to measure the amount of halo particles is the so-called longitudinal ‘bunch shaving’ during post-acceleration at 40 MHz in the PS [6]. Unlike in normal operation, the adiabatic RF manipulations, i.e. rephasing and bunch splittings, are performed on a magnetic plateau slightly below flat top. During the post-acceleration to flat top, the constant RF voltage at 40 MHz creates a bottleneck in the longitudinal acceptance and shaves off large synchrotron oscillation amplitude particles, which are then

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lost out of the RF bucket during post-acceleration. Finally, the shaved bunches are rotated and extrated to the SPS. The amount of shaving can be controlled by varying the 40 MHz RF voltage. By measuring the losses in the PS and SPS, it was found that the halo extends to a longitudinal emittance of 0.45 eVs [6], compared to the 0.35 eVs matched-area emittance [7].

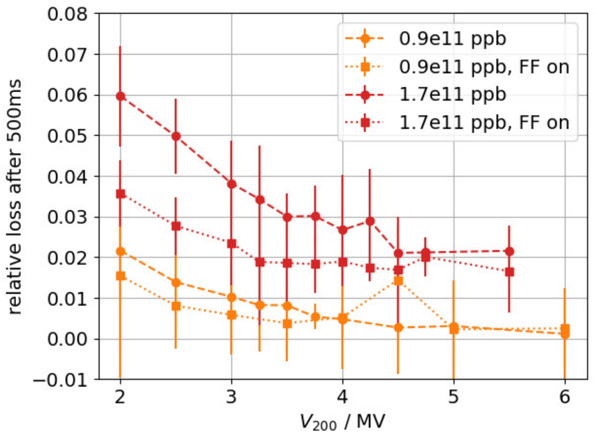

Figure 2: Capture losses of 72 bunches with feedback system on and feedforward system (FF) on or off as a function of the main RF voltage V_{200} for two different bunch intensities.

A second method to obtain information about the bunch halo is to measure the particle losses in the SPS as a function of RF bucket area, which is changed by varying the RF voltage V_{200} of the main Travelling Wave Cavities (TWC). Figure 2 shows the losses measured 500 ms after injection for a beam of 72 bunches, spaced 25 ns apart, for two different intensities. After 500 ms, most uncaptured particles have drifted away from the batch [6]. Losses are generally higher for the high-intensity beam (1.7×10^{11} ppb), because the intensity-dependent beam loading in the SPS decreases the available bucket area. If the losses were entirely due to intensity effects in the SPS, the curves for different intensities would be displaced horizontally, since the beam-loading could be compensated by a higher RF voltage. The *vertical* displacement then indicates that more halo particles are created in the PS at higher beam intensity. This effect is better seen for voltages above 3.5 MV, where the capture losses remain constant even for increasing RF bucket area. In this regime, the capture losses are dominated by the uncapturable halo particles delivered by the PS.

The effect of beam loading on losses is more pronounced for small V_{200}. To reduce beam loading, the SPS TWCs are equipped with feedback and feedforward (FF) systems. The one-turn delay feedback (OTFB) reduces the main impedance of the TWC by -15 dB and together with the FF reaches a reduction of -20 dB [8]. The dashed curves in Fig. 2 show the capture losses with only the OTFB active. Turning on the FF as well further reduces the capture losses. This effect is most pronounced for the high-intensity beam at small V_{200}, where the relative effect of beam loading is strongest. On the other hand, the FF does not decrease the losses for large voltages, as these are mainly due to the uncapturable halo particles delivered by the PS.

FLAT-BOTTOM LOSSES

The results presented in the previous section would suggest to operate at large RF voltage and with both OTFB and FF active. While these measures reduce the capture losses, further losses occur during the nominal LHC 11.2 s long flat bottom of the SPS. One source of flat-bottom losses is the limited momentum aperture of the SPS [9], which may touch the momentum acceptance. Because the bunch fills the entire RF bucket, particles with large momentum offset get lost [10].

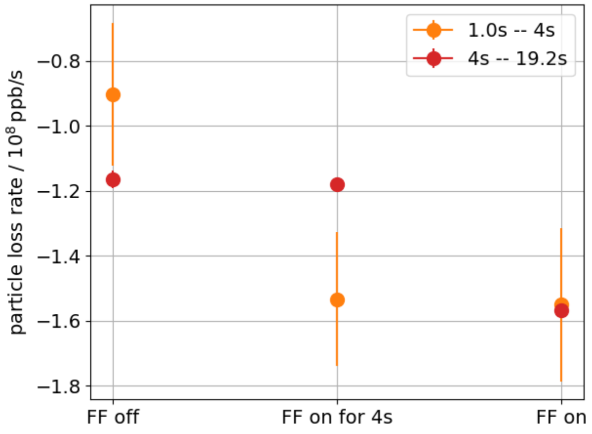

Figure 3: Particle loss rates during different parts of a 19.2 s long flat bottom. The feedforward (FF) was either entirely off, switched on for the first 4 s, or on during the entire cycle.

The feedforward system also injects RF noise, which drives particles out of the full RF bucket. This effect can be seen from Fig. 3, which shows the measured particle loss rate for different FF settings and 48 bunches with 1.2×10^{11} ppb on a 19.2 s exceptionally long flat bottom. The loss rate was obtained from a linear fit to the bunch intensity at flat bottom. For the first set of data, the FF was off during the entire time. For the second set, the FF was turned off four seconds after injection. Before the FF is turned off, the loss rate is -1.55×10^8 ppb/s, which is 33% larger than the loss rate without FF. After the FF is turned off, the loss rate returns to -1.16×10^8 ppb/s, which is the same value as without FF. Finally, when the FF is on during the entire cycle, the loss rate is again at -1.55×10^8 ppb/s.

Figure 4 shows the different contributions to the total flat-bottom losses for the various FF settings. Notice that the total losses are nearly identical for all three cases. When the FF is off, the capture losses are larger (blue boxes in Fig. 4). The flat-bottom losses from 1s up to the beginning of the ramp at 19.2 s are larger when the feedforward system is on (orange, green, and red boxes in Fig. 4). Particles still residing inside the RF bucket after capture when the FF is on

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are then lost on the flat bottom due to the RF noise injected by the FF. Losses occur when the feedforward system was turned off (green box of the middle column), because this change did not happen adiabatically. Finally, the losses at the beginning of the ramp occur, because the ramp can never be adiabatic for particles close to the separatrix, which are consequently lost (purple boxes in Fig. 4). Again, these losses are larger when the FF is off, because particles close to the separatrix were already driven out of the RF bucket during flat bottom when the FF was on.

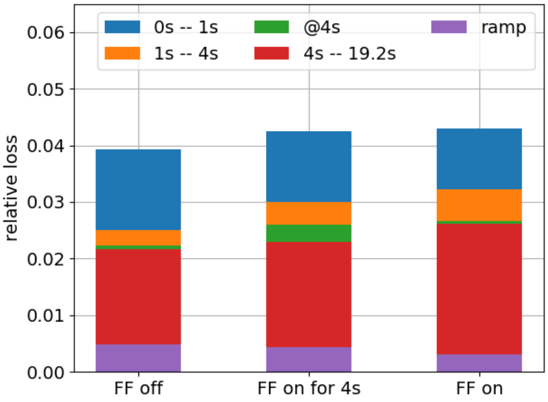

Figure 4: Relative losses during different parts (different colors) along the flat bottom for different feedforward (FF) settings. The capture losses occur from injection to 1 s, and the flat-bottom losses from 1 s up to the beginning of the ramp at 19.2 s. For the middle column, the FF was on during the first four seconds of the cycle.

LOSS MITIGATIONS

A number of mitigation measures for the capture and flat-bottom losses are planned during the ongoing Long Shutdown 2 (LS2). To reduce the amount of halo particles, the existing 40 MHz system in the PS can be modified to be operated as Landau cavities during the final part of the ramp [11]. This gives an additional margin to reduce the bunch emittance by 15% compared to the present 0.35 eVs at PS extraction. With the reduced injected emittance, the RF bucket will be less full after filamentation, which will improve the losses on flat bottom. Furthermore, the new digital LLRF system is expected to inject less RF noise. An impedance reduction campaign is implemented as well during LS2. Finally, physical aperture restrictions have been identified and will be removed during LS2 [9].

Several measures are taken in the SPS to reduce the beam loading. First, the number of sections per cavity is decreased to reduce the overall TWC impedance. The LLRF system will be upgraded as well [12]. On flat bottom, the present RF system is power limited for beams with more than 48 bunches and intensities larger than 1.7×10^{11} ppb and will be upgraded. The impedance reduction by the OTFB will increase from -15 dB to -26 dB and the present power limitation will be lifted. The beam phase loop presently takes only 12 bunches into account, but will measure all bunches after the upgrade.

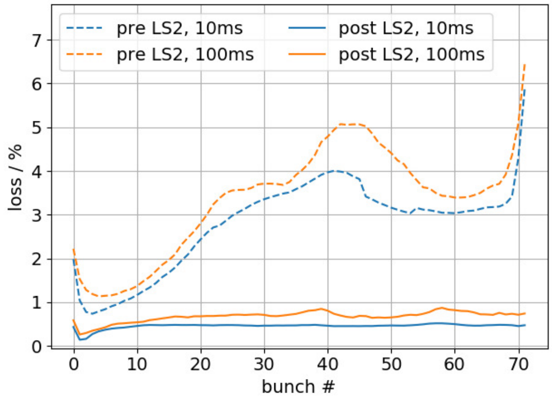

Figure 5: Simulated capture losses for 72 bunches with 2.6×10^{11} ppb in the present, pre-LS2 SPS (dashed curves) and the upgraded, post-LS2 SPS (continous).

The combined effect of all these improvements on simulated capture losses is shown in Fig. 5 for a batch of 72 bunches at 2.6×10^{11} ppb (for details of the simulation see [10]). While the quantitative amount of losses is strongly dependent on the assumption about the halo population, Fig. 5 shows that the capture losses are significantly reduced for the upgraded, post-LS2 SPS (continuous curve) compared to the present, pre-LS2 scenario (dashed curve). Notice that there is a strong bunch-by-bunch variation along the batch for the pre-LS2 scenario, due to the fact that beam loading is not fully compensated. In both cases, the majority of the capture losses occurs during the first 10 ms. For an estimate of the total losses, the beginning of the ramp needs to be included in future simulations.

CONCLUSION

For the SPS, the HL-LHC project requires beam with 2.6×10^{11} ppb at injection and a loss budget of not more than 10 %. Losses and instabilities during the cycle are major challenges in reaching these milestones. In this paper, we investigated the causes of losses that occur during the PS-to-SPS bunch-to-bucket transfer and at SPS flat bottom. Losses at capture arise from halo particles created in the PS and beam loading in the SPS. Losses along flat bottom are expected to decrease due to the reduced injected emittances, less RF noise, and removal of physical aperture limitations. With the foreseen improvements, these losses are expected to be significantly reduced and well within the loss budget.

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