STUDIES OF CAPTURE AND FLAT-BOTTOM LOSSES IN THE SPS

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Abstract

One of the strong limitations for reaching higher beam intensities in the SPS, the injector of the LHC at CERN, are particle losses at flat bottom that increase with beam intensity. In this paper, different sources of these losses are investigated for two available SPS optics, using both measurements and simulations. Part of the losses originate from the PS-to-SPS bunch-to-bucket transfer, because the PS bunches are rotated in longitudinal phase space before injection and do not completely fit into the SPS RF bucket. The injection losses due to different injected bunch distributions were analyzed. Furthermore, at high intensities the transient beam loading in the SPS has a strong impact, which is (partially) compensated by the LLRF system. The effect of the present and future upgraded one-turn delay feedback system and phase loop on flat-bottom losses was studied using the longitudinal tracking code BLonD. Finally, the total particle losses are also affected by limitations in the SPS momentum aperture, visible for higher RF capture voltages in optics with lower transition energy and higher dispersion.

INTRODUCTION

To achieve the luminosity planned by the High Luminosity LHC (HL-LHC) project at CERN, the injected beam intensity in the LHC needs to be 2.3×10^{11} protons per bunch (ppb) and requires an upgrade of the LHC and its injector chain. For the SPS, injector of the LHC, this requires an injected intensity of 2.6×10^{11} ppb, to account for the loss budget of 10% from injection to extraction [1]. These numbers require a doubling of the present nominal SPS beam intensity and are one of the targets of the LHC injectors upgrade (LIU) project. Extrapolating from measurements in 2015 with 2×10^{11} ppb and four batches to HL-LHC intensities, the expected losses could be as high as 20% [2]. Reaching the required 2.3×10^{11} ppb at extraction while staying within the loss budget is challenging and requires a better understanding of the origin of particle losses in the SPS. In this paper, we focus on the analysis of losses during capture and along the flat-bottom.

Capture losses are mainly caused by halos of the bunch distribution delivered by the PS, the injector of the SPS. Several techniques have been studied recently to measure and reduce the longitudinal bunch halo [3]. We studied these losses experimentally by varying the beam intensity and RF bucket area. Measurements are compared to simulations with different initial beam distributions. The simulations were done using the full SPS longitudinal impedance model [4] and several settings of the low-level RF (LLRF) system. But even after the halo particles are lost, the bunches continuously lose particles along the flat bottom. We also present measurements of these flat-bottom losses for different momentum apertures.

MEASUREMENT SETUP

All measurements were done with a single batch of either 48 or 72 bunches, spaced by 25 ns. The RF bucket area was changed by varying the voltage V_{200} of the main 200 MHz Traveling Wave Cavities (TWC). We employed two methods to measure the beam intensity. The first uses a DC Beam Current Transformer (BCT), which yields an absolute number of particles. But it measures the beam current in the ring, and thus does not distinguish between particles captured in the RF buckets and uncaptured particles that still travel in the ring. Moreover, it is not fast enough to resolve the intensity during the first few milliseconds and, therefore, cannot resolve the injected intensity, which is crucial to measure the capture losses. As a second method, we observe the longitudinal bunch profiles with a wall current monitor and an oscilloscope. This allows for a measurement of the bunch-by-bunch intensity on a turn-by-turn basis by integrating the bunch profiles. The intensity was calibrated by the BCT intensity after uncaptured particles were removed either by a tune kicker or acceleration. Unless noted otherwise, all measured intensities and derived quantities were obtained from the integrated bunch profiles. Figure 1 shows beam intensities measured by the BCT (blue) and computed from the integrated bunch profiles (orange). Here, capture losses were enhanced by reducing the main RF voltage and result in a sharp decrease of the beam intensity during the first few

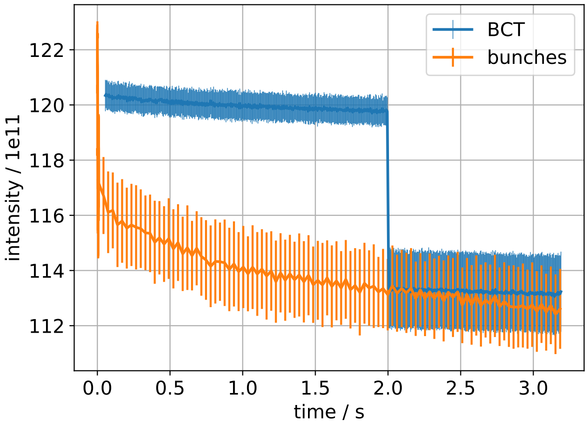

Figure 1: Beam intensity (number of protons), measured by the BCT (blue) and from the integrated bunch profiles (orange). A kick is applied at 2 s to remove the uncaptured particles.

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milliseconds. Because the particles lost out of the RF bucket are still circulating in the machine, the BCT intensity is above the bunch intensity until the lost particles are removed by a tune-kick at 2 s. Notice that the bunches continue to lose particles. It is important to keep in mind that the bunch profile is only a projection of the longitudinal phase space distribution and, hence, uncaptured particles below or above the RF bucket are counted as well.

SIMULATION SETUP

Correct simulations of the losses in the SPS require both an accurate initial beam distribution as well as a model of the LLRF system. For our simulations we used the longitudinal tracking code BLonD [5]. Besides being able to compute the effects of the beam induced voltage, BLonD can model beam-based feedbacks.

Initial Beam Distribution

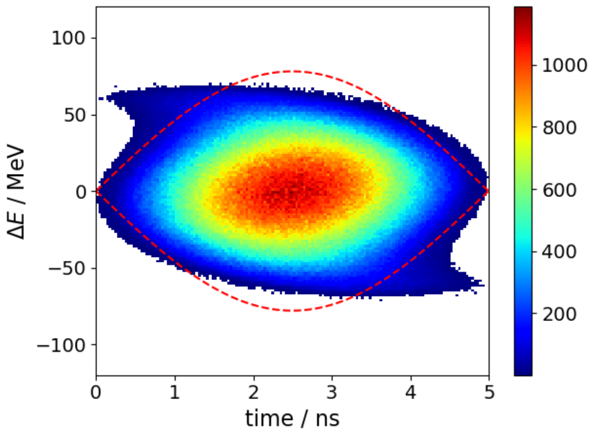

Figure 2: Simulated PS particle distribution with 1.1% of particles in a halo outside the SPS RF bucket (red dashed curve).

Before the bunches are injected into the SPS, they are subject to several RF manipulations in the PS. First, the initial six bunches are split several times to the final number of 72 bunches. With a 4σ bunch length of 14 ns, these bunches do not fit into the 5 ns long SPS RF bucket. As a last step, a bunch rotation is performed in the PS to decrease the bunch length down to 4 ns. However, due to the nonlinearity of the RF voltage, a bunch halo is created that is outside the SPS RF bucket [6].

To vary the initial particle distribution, we simulated the bunch rotation in the PS for different cases, to produce bunches with different halos. In this paper, we characterize the halo by the percentage of macro-particles that are outside the SPS RF bucket. For an RF voltage of 2.0 MV, the three different initial distributions have 0%, 0.3% and 1.1% of the particles outside the RF bucket, see Fig. 2 for an example. Without any beam loading, this would also be the amount of particles lost. In reality losses are higher due to intensity effects in the SPS. The single simulated PS bunch has four million macro-particles. To create an SPS beam of 72 bunches, we randomly selected 1.5 million macro-particles 72 times and placed them at the center of the SPS bucket, 25 ns apart. The simulations were repeated with different seeds of the random number generator, but yielded nearly identical results.

Modeling of the SPS LLRF System

Due to intensity effects, the SPS RF bucket area is reduced. To take these effects into account, we use the present SPS impedance model in our simulations. It covers frequencies up to 6 GHz [4, 7] and is dominated at low frequencies by the impedance of the main harmonic of the 200 MHz TWC. Presently, the SPS has two 'short' and two 'long' TWCs with an effective length of 16.082 m and 20.196 m, respectively. Their impedance $Z_{TWC}(\omega)$ can be calculated analytically [8]. To reduce the effective impedance experienced by the beam, each of the four TWCs is equipped with a feed-forward and a one-turn delay feedback system (OTFB) [9]. In this paper, we only model the effect of the OTFB and the feed-forward system was turned off during measurements. A BLonD model for the OTFB is presently under development [10]. Here, we model the effect of the OTFB by its effective impedance reduction factor $\Gamma(\omega)$. In the SPS, the OTFB includes a comb filter to mainly act at multiples of the revolution frequency [9], while in our model we consider only the envelope. The full impedance reduction $\Gamma(\omega)$ is reached only after a transient time τ_{FB}. We model this transient by a time dependent attenuation $a(t)$, i.e. at turn n the impedance of the TWC is given by

$$Z_{TWC,n}(\omega) = Z_{TWC}(\omega)\,\Gamma(\omega)^{a(n\,t_{\mathrm{rev}})}\,. \qquad (1)$$

The attenuation is modeled as $a(t) = F_{FB}\left[1 - \exp(-(t - t_0)/\tau_{FB})\right]$ and starts at time t_0. At t_0 the attenuation is zero and the impedance in Eq. (1) is not reduced. The attenuation then increases exponentially with time constant τ_{FB} to the final value of F_{FB}.

We adjust the free parameters F_{FB}, τ_{FB} and t_0 by comparing the simulated induced voltage V_{ind} with the measured one. The cavity induced voltage is measured at the RF frequency and the simulated voltage is, therefore, filtered at this frequency. At each turn, the maxima of V_{ind} from measurement and simulation are then compared. The result for 48 bunches and V_{200} of 4.5 MV is shown in Fig. 3. The first turn is without beam and thus no induced voltage. Once the beam is present, the induced voltage reaches its maximum value and is then reduced. Notice that the induced voltage is larger in the 'long' cavity, since it depends on the square of the cavity length [8]. The parameter F_{FB} controls the asymptotic value of the impedance reduction, which is reproduced well by the model.

With just the OTFB included in the simulations, the time dependence of the beam intensity is well reproduced, but simulated losses are two- to three times higher compared to measurements. Besides the OTFB, a beam phase loop is also active in the SPS. The phase loop corrects phase

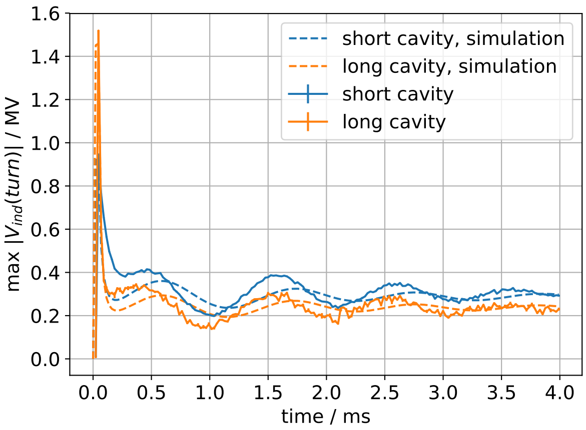

Figure 3: Comparison between measured (continuous lines) and simulated (dashed) maximum induced voltage after injection in the short and long 200 MHz TWCs.

or energy errors of the injected beam by changing the RF frequency. It compares the measured stable beam phase to its reference value. In the SPS, the beam phase is obtained by averaging over the first twelve bunches and the reference phase derived from the momentum program (without beam loading). Since the induced voltage changes the stable phase, the result is that the beam is not centered in the RF bucket. A synchronization (frequency) loop is used in the SPS to center the beam in energy. It is modeled as a frequency loop in BLonD that locks the RF frequency onto the design value.

To compare the losses in simulation to measurements, we computed the losses from the simulated bunch profiles.

LOSSES AT CAPTURE

Figure 4 shows the measured beam intensity during the first 9 ms (corresponding to about 400 turns in the SPS) for a beam of 72 bunches with 1.7×10^{11} ppb and an RF voltage V_{200} of 2.0 MV. This voltage is less than the nominal 3.5 MV and was chosen to enhance the losses at injection. The intensity quickly drops as the halo of particles, which are outside the RF bucket, drift away. After about 350 turns (8 ms) these uncaptured particles drift above or below the RF bucket of a neighboring bunch and the intensity increases again. The simulations differ in the initial macro-particle distribution used. Due to beam loading, even a distribution that would fit entirely into the 'bare' SPS RF bucket (0% halos) has losses of about 3%. The amount of losses increases with increasing halo, but the overall shape of the curve remains similar. As can be seen from the simulations, however, the total amount of particles lost depends strongly on the halos.

The distribution of the losses along the batch can be seen in Fig. 5, where we compute the amount of particles lost for each bunch. Already after 1 ms (43 turns) the bunches at the end of the batch have lost twice as much than those at the head, since the beam loading increases along the batch. The beam loading builds up over a distance related to the filling time of the TWCs, which is about 700 ns, covering 28 bunches. Indeed, Fig. 5 shows a general increase in losses for the first 30 bunches after 10 ms. The fact that the losses are roughly constant for the first twelve bunches is due to the phase loop, which adjusts the RF frequency using the phases of the first twelve bunches.

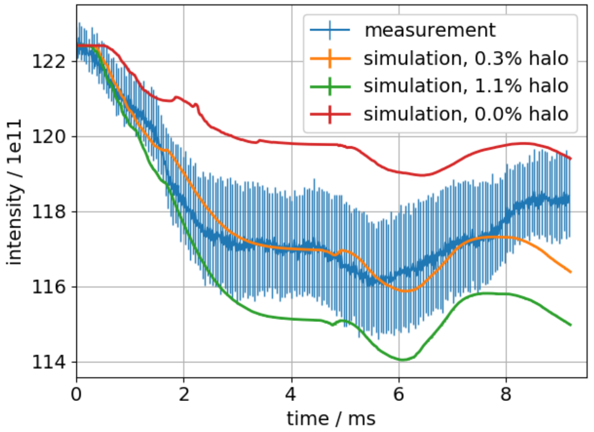

Figure 4: Measured beam intensity (blue) for a beam of 72 bunches with 1.7×10^{11} protons per bunch and V_{200} of 2.0 MV. Simulations were performed for three particle distributions with different halos.

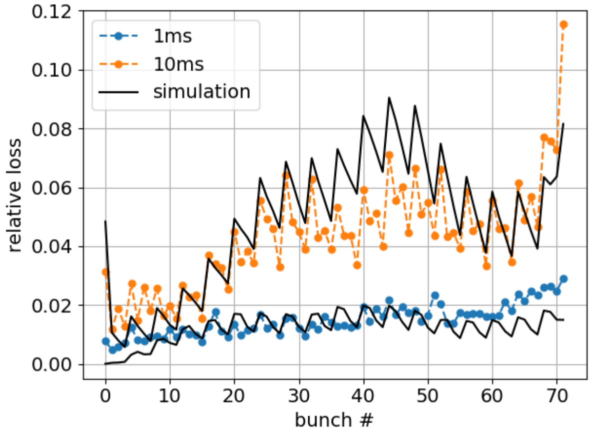

Figure 5: Measured relative particle losses along the batch at 1 ms and 10 ms after injection for the case of Fig. 4. Simulation results are shown by black lines.

The measured loss pattern also displays a strong modulation, with a period of four bunches. It results from an imperfect bunch splitting process in the PS, which leads to a modulation of both the bunch length and the intensity along the injected batch. In simulations with 72 identical bunches, the resulting loss pattern follows the measured pattern, but does not display the modulation. When we use a beam where the intensity of the bunches is modulated along the batch (keeping the bunch length constant), the simulated loss pattern does display the same modulation, but the variation from bunch to bunch is not as large as observed. The measured loss pattern can be reproduced in simulations only when four bunches with different bunch lengths are used and repeated along the batch, see black curves in Fig. 5. This also shows that for losses a control of the injected bunch-by-bunch bunch length is more important than a control of the intensity variation.

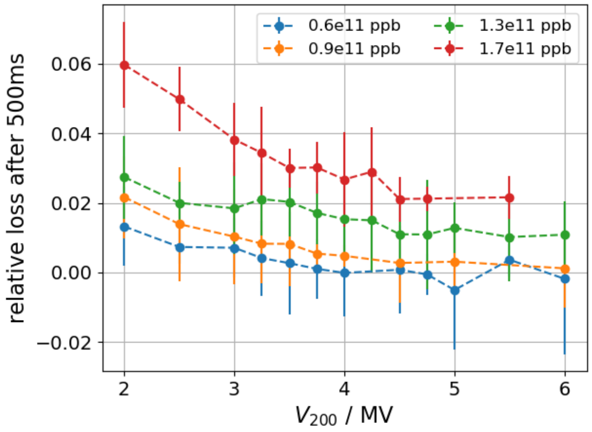

Figure 6: Measured relative particles losses for different V_{200} and different protons per bunch (ppb) for a beam of 72 bunches at 500 ms after injection. Data points joined to guide the eye.

The uncaptured beam has drifted away from the batch after 500 ms [3]. To measure the capture losses, we, therefore, compare the beam intensity at injection to the beam intensity after 500 ms. By changing the voltage V_{200} of the 200 MHz TWC at injection, the available RF bucket area is changed as well. Figure 6 shows the capture losses as a function of V_{200} for bunch intensities between $(0.6 - 1.7) \times 10^{11}$ ppb. Losses decrease for increasing V_{200} but reach a plateau value above ~4.5 MV. Above this voltage, the main bunch and most of its halo are captured inside the RF bucket and increasing the RF voltage V_{200} further does not reduce the capture losses (but does affect the losses on the flat-bottom, see next section). If the bunch distributions injected from the PS were not depending on intensity, the loss curves for different intensities were shifted horizontally towards higher V_{200}, since more RF voltage is needed to compensate the increased beam loading. However, Fig. 6 shows a *vertical* offset with increasing bunch intensity. With higher intensity, a larger halo is created in the PS, that cannot be captured inside the SPS RF bucket. The effect of beam loading becomes more evident for smaller V_{200} and higher intensities, because its relative effect, as compared to the main RF voltage, increases for lower V_{200}. Hence, the RF bucket area is reduced and the losses increase.

LOSSES ALONG FLAT BOTTOM

If the losses along the entire flat bottom were solely due to the particles lost at injection, Fig. 6 would suggest to use the maximum capture voltage to reduce the particle losses. If this was done right at injection, it would lead to a large emittance due to beam filamentation, which would be difficult to accelerate. Instead, we injected the beam with nominal voltage of 4.5 MV and changed the voltage 50 ms after injection during a 100 ms short ramp. At the end of the flat-bottom, another ramp was used to bring the voltage back to the nominal value. Figure 7 (top) shows the measured intensity when the voltage was decreased to 3.0 MV. Since the RF bucket area is reduced, the bunches lose particles and their intensity decreases. But they are still present in the SPS, since the intensity measured by the BCT does not decrease. Notice that the bunches continue to lose particles along the flat-bottom. When the RF bucket area is increased by increasing the voltage to 7.0 MV, see Fig. 7 (bottom), the bunches initially lose significantly less particles. However, the particle loss rate along the flat bottom is increased by about 50% and the final intensity after acceleration is 1% less compared to the case when the voltage was reduced.

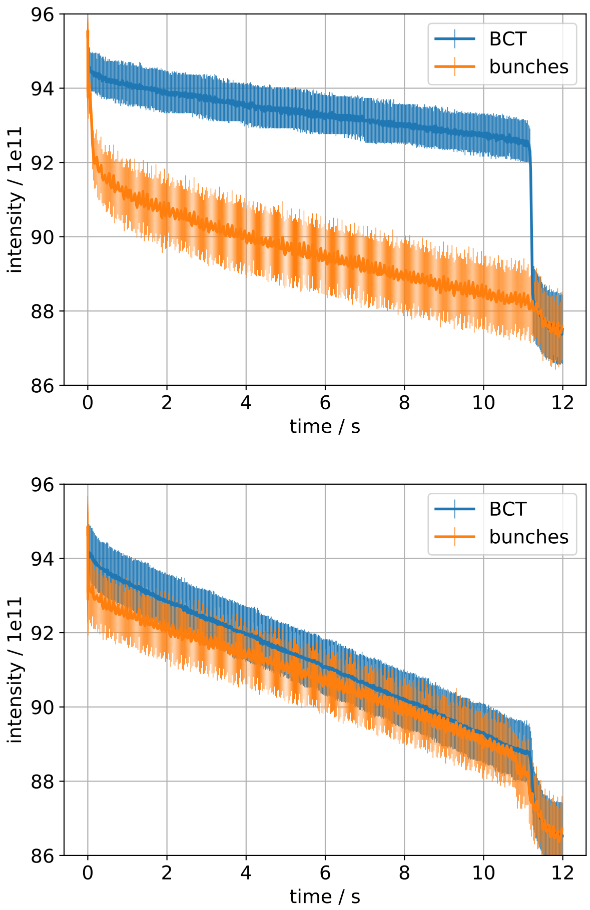

Figure 7: Measured beam intensity during 12 s. The voltage was changed from its nominal value of 4.5 MV to either 3.0 MV (top) or 7.0 MV (bottom) at 50 ms after injection.

These findings can be explained by the limited momentum aperture of the SPS. By increasing V_{200}, the momentum acceptance of the RF bucket is increased. Particles with large momentum-offsets now touch the momentum aperture and get lost. To further study the effect of the momentum

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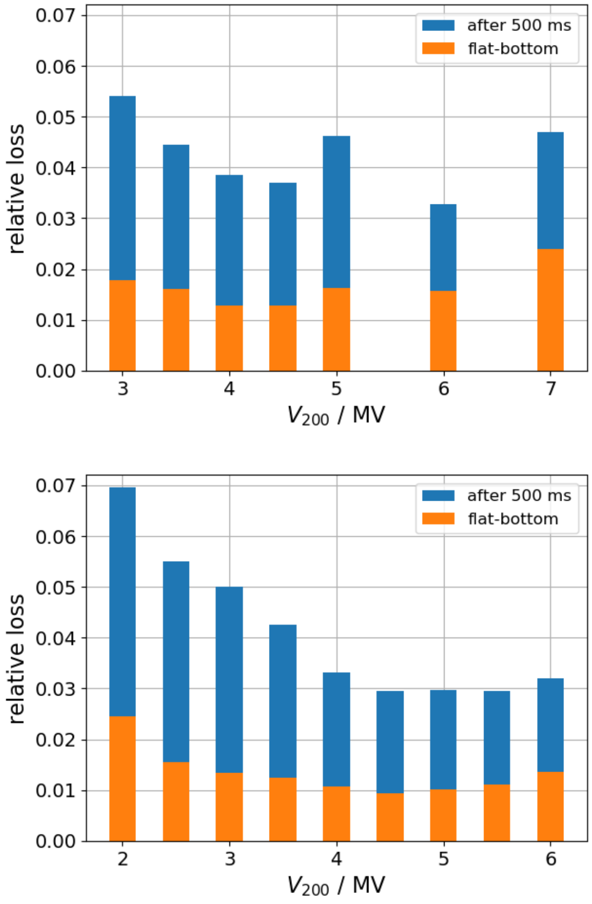

Figure 8: Measured relative particle losses at 500 ms after capture (blue) and during the following 9.5 s of flat bottom (orange) for a beam of 48 bunches in nominal optics ‘Q20’ (top) and an optics with larger momentum aperture ‘Q22’ (bottom).

aperture on the flat-bottom losses, we compared the losses along an 11.1 s long flat-bottom with nominal optics ‘Q20’ to losses in the optics with larger momentum aperture ‘Q22’. This optics has an increased transition energy and, hence, a larger RF bucket area for a given RF voltage. Equivalent voltages that yield the same RF bucket area are related by $V_{Q22} \simeq 0.81 V_{Q20}$. For equivalent voltages, we observed a reduction in losses by about 1% for intensities below and up to nominal intensities. For higher intensities, and increased beam loading, the losses were comparable.

Figure 8 shows the losses for a beam of 48 bunches with 1.3×10^{11} ppb and a reduced transverse emittance in both optics for different voltages. The losses at 500 ms after injection decrease for higher RF voltage, which is consistent with the increased RF bucket area capturing more halo particles. A minimum in total losses occurs for the nominal 4.5 MV. For higher voltages, the total losses increase again due to the increased loss along the flat bottom. In addition, the flat-bottom losses in the nominal ‘Q20’ optics at 7.0 MV are about twice as high for the equivalent voltage of 5.7 MV in the ‘Q22’ optics with increased momentum aperture.

CONCLUSION

Particle losses in the SPS are a bottleneck to reach the beam intensities required for the HL-LHC era. Here, we studied two sources of losses that occur at the SPS flat bottom. The first loss occurs at the PS-to-SPS bunch-to-bucket transfer. Halo particles outside the SPS RF bucket are lost. This effect increases with intensity both due to the increased SPS beam loading and bunch distributions from the PS with larger halos. Reproducing these losses in simulations requires modeling the LLRF system. We modeled the effect of the one-turn feedback by its effective impedance reduction. Quantitative agreement with measurements was obtained by including the phase loop as well as the frequency loop. The simulations show a strong sensitivity of the capture losses on the initial bunch distribution.

With an accurate simulation model of the capture losses, we simulated the future high-luminosity beam of 72 bunches with 2.6×10^{11} ppb. With the present, not upgraded, SPS this intensity would lead to capture losses of 6%. Several improvements to the SPS are foreseen within the LIU project. They include the longitudinal impedance reduction of vacuum flanges, an upgrade of the OTFB to obtain an impedance reduction of -26 dB (compared to the present -15 dB), a beam phase loop taking into account all 72 bunches (instead of just twelve), and shorter lengths of the main RF cavities to reduce beam loading. When these future parameters are used in simulations, the capture losses are below 2%.

While the capture losses can be reduced by increasing the RF voltage, the losses along the entire flat bottom are not reduced. One reason for this was found to be the limited momentum aperture. We measured the flat-bottom losses for beams in nominal optics and an optics with increased momentum aperture. For high voltages the flat-bottom losses are reduced by 50% in the optics with larger momentum aperture (‘Q22’). A physical aperture limitation for the ‘Q20’ optics was recently discovered [11], and will be fixed during the upcoming long shutdown to help to improve the flat-bottom losses. RF noise as another source of flat-bottom losses is presently under investigation.

The effect of the momentum aperture limitation is currently not implemented in the simulation code. While this is sufficient for the simulation of the capture losses, it needs to be included to simulate the beam behavior at longer time scales.

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