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SIMULATION STUDIES OF LONGITUDINAL STABILITY FOR HIGH-INTENSITY LHC-TYPE BEAMS IN THE CERN SPS

D. Quartullo*, L. Intelisano, I. Karpov, G. Papotti, CERN, Geneva, Switzerland

Abstract

Beams in the SPS for the High Luminosity LHC (HL-LHC) must be stabilized in the longitudinal plane up to an intensity of $2.4 \cdot 10^{11}$ protons per bunch. The fourth harmonic RF system increases Landau damping, and controlled longitudinal emittance blow-up is applied to cope with coupled-bunch instabilities along the ramp and at flat-top. Longitudinal multi-bunch beam dynamics simulations of the SPS cycle were performed starting from realistic bunch distributions, as injected from the PS. The full SPS impedance model was included, as well as the effect of low-level RF (LLRF) feedback for beam-loading compensation. A realistic model of the beam-based LLRF loops was used for the particle tracking studies. Controlled longitudinal emittance blow-up was included by generating bandwidth-limited RF phase noise and by injecting it into the beam phase-loop input, exactly as in hardware. Due to the stringent constraints on particle losses and extracted bunch lengths, particular attention was paid to monitoring these parameters in the simulations, and to determining the best configuration for a stable acceleration of the beam.

INTRODUCTION

High-intensity proton beams in the SPS for the High Luminosity LHC (HL-LHC) require stabilization in the longitudinal plane to cope with coupled-bunch instabilities during the ramp and at the flat-top [1–3]. The voltage of the 200 MHz main RF system will be larger than the one currently used for LHC-type beams. A fourth-harmonic RF system is applied to increase the synchrotron frequency spread inside the bunch enhancing Landau damping [4]; bandwidth-limited RF phase noise blows up the longitudinal emittances of the distributions in a controlled way during the cycle [5–7].

The target injected bunch intensity for the four batches of 72 bunches is $N_\mathrm{p} = 2.4 \cdot 10^{11}$ p/b (protons per bunch). Stringent requirements on particle losses and extracted bunch lengths have to be fulfilled: the total losses along the cycle should be less than 5% of the injected intensity, while the extracted bunch lengths must be around 1.65 ns, with a maximum spread of 10%. Indeed, shorter bunches will be unstable in the SPS [2], while longer bunches will not fit into the 400 MHz RF buckets of the LHC.

Longitudinal beam dynamics simulations for present or HL-LHC beams in the SPS have been performed recently [2, 8, 9]. However, the previous studies at injection energy used simplified models of the Low Level RF (LLRF) beam-based loops and of the One-Turn Delay Feedback (OTDFB) for beam loading compensation [8, 9].

* danilo.quartullo@cern.ch

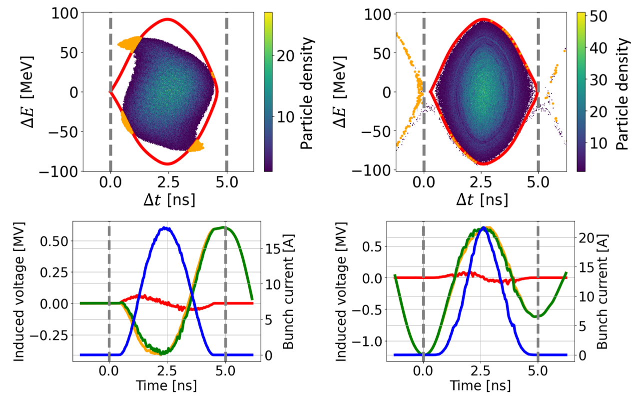

Figure 1: Top: distributions of bunch 1 at injection (left) and after 0.5 s (right). The particles marked in orange are outside the separatrix (red). Bottom: corresponding profiles (blue). The total induced voltage (green) is the sum of the induced voltage from the impedance model (orange) and the space-charge voltage (red). The grey lines mark the RF period.

In addition, tracking simulations along the ramp assumed constant longitudinal emittance [2].

This contribution presents refined simulations of HL-LHC beams in the SPS. One main goal of this study is to verify that the requirements mentioned above can be satisfied.

SIMULATIONS AT INJECTION ENERGY

For the studies at 26 GeV/c, one batch of 72 injected bunches with $N_\mathrm{p} = 2.4 \cdot 10^{11}$ p/b was tracked for 0.5 s using the CERN BLonD code [10]. The injected bunch distributions (Fig. 1, top left) were obtained by performing tracking simulations at PS flat-top [11, 12], including collective effects and assuming all the PS RF upgrades for the HL-LHC scenario. However, bunch-by-bunch emittance and intensity spreads were not considered. In simulations at SPS injection energy, the voltages of the 200 MHz and 800 MHz RF systems were respectively 4.5 MV and 0.45 MV. These voltages are currently applied to LHC-type beams at SPS flat-bottom.

The full SPS impedance model [2] was included in simulations, the space charge impedance had $\mathrm{Im}(Z)/n = -1\,\Omega$ [13]. The effect of the OTDFB was added by applying its transfer function [14, 15] to the longitudinal impedance of the 200 MHz and 800 MHz RF cavities (Fig. 2), using the nominal feedback gain of 26 dB. To resolve the notches of the OTDFB transfer function, the frequency resolution of the impedance was set to $\Delta f = f_0/50$, where f_0 is the revolution frequency. This corresponds to keeping in memory wake-fields extending for 50 turns.

An accurate model of the beam-based loops [16, 17] was adopted. The loop gains were set to the values presently in

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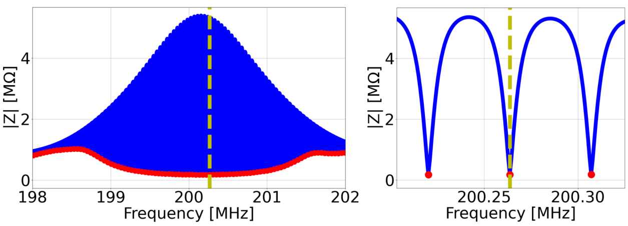

Figure 2: Left: impedance sum (blue) of the six SPS accelerating RF cavities damped with their OTDFB systems. The frequency resolution is $\Delta f = f_0/50$. The red dots are the minima of the notches and represent the impedance sum with $\Delta f = f_0$. The yellow line marks the design RF frequency at injection energy. Right: zoom around the RF frequency.

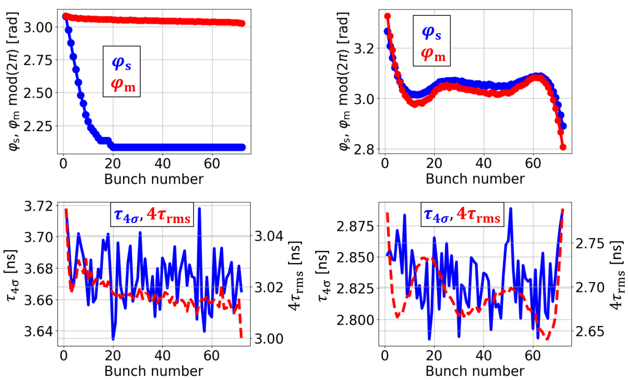

Figure 3: Top: average of the bunch profile (red) and synchronous phase (blue) along the batch at injection (left) and after 0.5 s (right). Bottom: $\tau_{4\sigma}$ (blue) and $4\tau_{\mathrm{rms}}$ (red) along the batch at injection (left) and after 0.5 s (right).

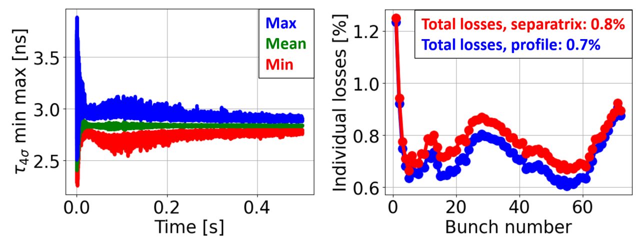

Figure 4: Evolution of maximum, mean and minimum $\tau_{4\sigma}$, out of 72 bunches. Right: losses along the batch at 0.5 s, either counting the particles outside the separatrix with respect to the injected intensity (red), or evaluating the decrease in bunch current relative to the injected current (blue). The total losses for the 72 bunches are reported in the legend.

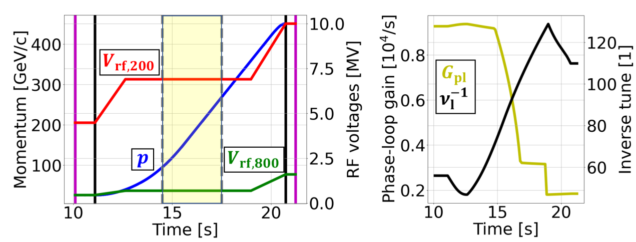

Figure 5: Left: momentum program (blue) together with the voltage programs of the 200 MHz (red) and 800 MHz (green) RF systems. The magenta (black) lines mark the start and the end of the simulations (ramp). The shaded area indicates the time interval for controlled emittance blow-up. Right: phase-loop gain (yellow) and number of turns per synchrotron period (black) along the cycle.

operation for LHC-type beams. The phase-loop delay and the initial RF phase were optimized to center the mismatched bunches in the RF buckets, while minimizing overshoots of beam-loop frequency corrections due to collective effects.

Simulation results confirm the strong impact of the cavities impedance reduced by the OTDFB. For instance, the induced voltage of bunch 1 at injection is essentially resistive, and at equilibrium it approximately changes sign due to the action of the OTDFB (Fig. 1, bottom).

At injection, the profile averages have a low spread along the batch and depend on the beam dynamics at PS flat-top (Fig. 3, top left). The spread is larger for the synchronous phases, which are computed as minima of potential wells and which depend on the SPS impedance model. At 0.5 s, the dynamics is dominated by the OTDFB (Fig. 3, top right), with almost overlapping profile averages and synchronous phases. The first few bunches with $\varphi_s > \pi$ experience an overcompensation from the OTDFB.

In the SPS, the bunch length $\tau_{4\sigma}$ is computed from the Full Width at Half Maximum (FWHM) of the profile by rescaling to 4σ of a Gaussian line-density. The simulated $\tau_{4\sigma}$ are 3.7 ns and 2.8 ns at injection and after 0.5 s, respectively (Fig. 3, bottom). Bunch-length trends along the batch are better defined computing the second moment τ_{rms} of the profiles, since the rms integrates over the entire line density.

The simulated beam reaches a steady state after 0.5 s (Fig. 4, left). Particle losses along the batch are evaluated using two methods giving very similar results, as shown in Fig. 4 (right). The first bunch has the largest number of losses, the total simulated losses are below 1%.

SIMULATIONS DURING THE CYCLE

Simulations of one batch of 72 bunches with $2.4 \cdot 10^{11}$ p/b started 1 s before the beginning of the ramp and ended at extraction (Fig. 5, left). Even if only 1 s out of the entire 11 s long flat-bottom was simulated, the initial distributions were the ones used for the studies at injection (Fig. 1, left).

The momentum program was the one currently used for LHC-type beams, while the 200 MHz voltage program was the one designed for HL-LHC intensity: 6.9 MV along a large portion of the ramp and 10 MV at flat-top (Fig. 5, left). The ratio between the two RF systems was 10% until 19 s and raised to 16% at flat-top. The voltage programs were defined based on beam loading and stability analysis [18]. The gains of the phase, synchro and frequency loops were according to present operational conditions (Fig. 5, right). For computational reasons, we could not evaluate multi-turn wake-fields for the cavities impedance with the OTDFB. With $\Delta f = f_0$, only the minima of the resolved impedance

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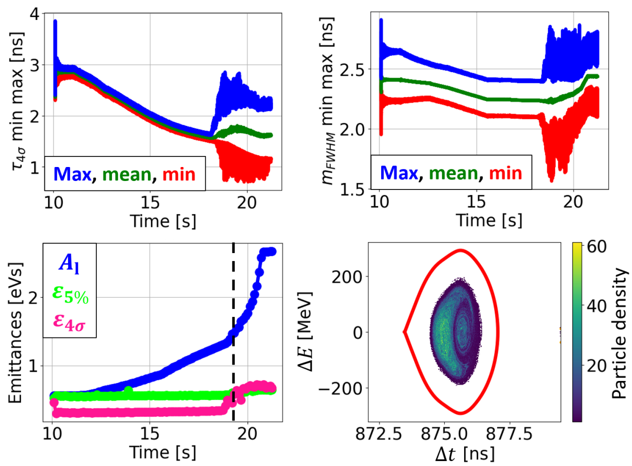

Figure 6: Top: evolution of maximum, mean and minimum $\tau_{4\sigma}$ (left) and profile position (modulo the RF period) computed as middle point of FWHM (right), out of 72 bunches. Simulation without controlled emittance blow-up. Bottom left: bucket area (blue), $\epsilon_{5\%}$ (green) and $\epsilon_{4\sigma}$ (magenta) of bunch 36 along the cycle. The black line marks 19.2 s. Bottom right: phase-space distribution of bunch 36 at 19.2 s.

are considered (Fig. 2). This simplification over-estimates the compensation of the beam loading.

Without controlled emittance blow-up, the simulated beam becomes unstable in the last part of the ramp (Fig. 6, top). The 22$^{\text{nd}}$ to 63$^{\text{rd}}$ bunches, located in the steady-state part of the batch (Fig. 3, top right), are the ones most affected by the instability (Fig. 6, bottom).

The bunch longitudinal emittances were also evaluated. For a given profile, the limits where the amplitude was 5% of the peak determined the Hamiltonian defining the $\epsilon_{5\%}$ emittance. Similarly, the emittance $\epsilon_{4\sigma}$ was derived by the profile limits defined by $\tau_{4\sigma}$. As Fig. 6 (bottom left) indicates, $\epsilon_{5\%}$ is preserved along the cycle, while $\epsilon_{4\sigma}$ increases, indicating that the instability affects the bunch core, but not the tails. No losses are observed, since the bunch tails are not diffused and the bucket area is sufficiently large.

To avoid the beam instability along the ramp, controlled emittance blow-up was included in simulations by applying RF phase noise between 14.5 s and 17.5 s. A dedicated algorithm [6] for frequency-band determination provided the optimal normalized lower and upper frequencies, which were respectively set to 0.7 and 1 during the blow-up. The phase-noise rms amplitude was set to 0.93 deg to obtain the requested average bunch-length of 1.65 ns at extraction.

Figure 7 (top) shows that the simulated beam is stable along the cycle. The average $\tau_{4\sigma}$ at extraction (Fig. 7, bottom right) is 1.66 ns with a maximum spread of 4%, therefore the requirements are satisfied. No losses are observed, since phase noise diffuses only the bunch core (Fig. 7, bottom left). The distributions at extraction do not present signs of beam-quality degradation (Fig. 8, left). As desired, the profiles are almost parabolic, since they can be fitted with binomial line-densities having exponent $\mu \approx 1$ (Fig. 8, right).

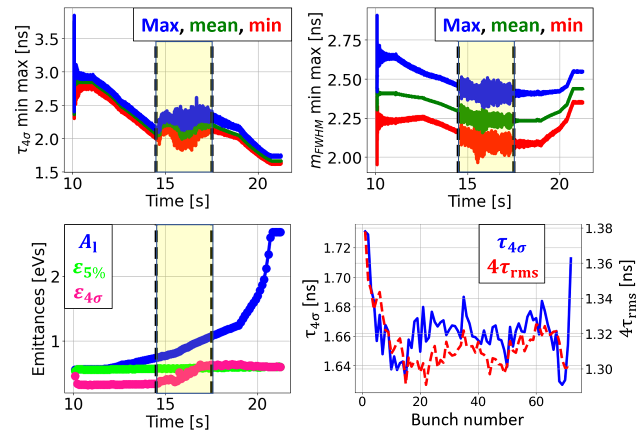

Figure 7: Top and bottom left: same color legends as in Fig. 6. The shaded area indicates the time interval for controlled emittance blow-up. Bottom right: extracted $\tau_{4\sigma}$ (blue) and $4\tau_{\text{rms}}$ (red) along the batch.

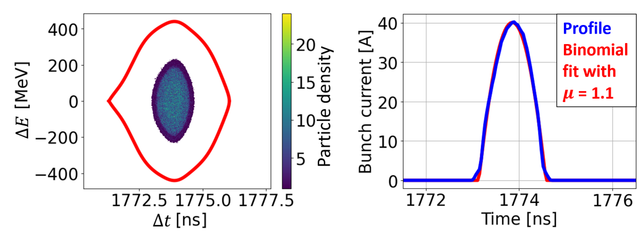

Figure 8: Distribution (left) and profile (right) of bunch 72 at extraction, applying controlled emittance blow-up as shown in Fig. 7. The binomial fit of the profile results in $\mu = 1.1$.

CONCLUSIONS

Longitudinal-dynamics simulations of one batch of 72 bunches at HL-LHC intensity of $2.4 \cdot 10^{11}$ p/b were performed at SPS flat-bottom and along the ramp. Compared to previous studies, these simulations adopted a more reliable model of the OTDFB, more accurate implementations of the beam-based loops and controlled emittance blow-up.

Simulations at injection energy show that the captured beam remains stable. At equilibrium, the bunch-length spreads and losses are below 3% and 1%, respectively. For the simulations along the ramp, we first verified that the beam is unstable without controlled emittance blow-up, as observed with beam for lower intensities in the SPS. Using controlled emittance blow-up, the beam is stable, and the average bunch length at extraction is 1.7 ns, with spreads below 5%. The profiles at extraction are almost parabolic, indicating that phase noise diffuses only the bunch core. No losses are observed during the ramp. In conclusion, the simulated beam is stable along the cycle, and the requirements on losses and bunch lengths are satisfied with some margin.

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