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LONGITUDINAL STABILITY OF THE HOLLOW ION BUNCHES AFTER MOMENTUM SLIP-STACKING IN THE CERN SPS

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Abstract

Momentum slip-stacking is planned to be used for the lead ion beams in the CERN SPS to double the beam intensity for the High-Luminosity LHC project. During this RF manipulation, two SPS batches, controlled by two independent RF systems, are going to be interleaved on an intermediate energy plateau, reducing the bunch spacing from 100 ns to 50 ns. However, there are limitations how close the frequencies of the two RF systems can approach each other, resulting in a hole in the longitudinal bunch particle distribution due to the offset in energy of the recaptured bunches. After filamentation, these bunches should be further accelerated to the SPS top energy, before extraction to the LHC. Macro-particle simulations have shown that Landau damping is lost for the bunches with the smallest longitudinal emittances in the batch, causing un-damped oscillations of the bunch core after recapture. The standard application of an additional, fourth harmonic RF system, successfully used in proton operation, was not able to damp the oscillations at top energy, and it is necessary to switch it on from the moment of recapture. In this paper the longitudinal stability of the bunches after slip-stacking is studied using both macro-particle simulations and analytical calculations.

INTRODUCTION

The Momentum Slip-Stacking (MSS) technique is planned to be used for the LHC ion beams in the SPS after the Long Shutdown 2 (LS2) in 2021, to reduce the bunch spacing from 100 ns to 50 ns and therefore to increase the total beam intensity in the frame of the LHC Injectors Upgrade (LIU) project [1]. This complicated beam manipulation is going to take place in an intermediate energy plateau at 300 ZGeV/c (γ=127), in a specifically designed magnetic cycle. Currently, in the SPS, the LHC Pb82$^+$ ion beams are accelerated from 17 ZGeV/c (γ=7) to 450 ZGeV/c (γ=191).

A detailed description of the MSS process, as planned to be implemented in the SPS, can be found in [2]. Two SPS batches of 24 bunches, spaced by 100 ns, are going to be captured by two independent RF systems. By introducing a small difference in the frequencies of the two RF systems, the two batches start approaching each other longitudinally, due to the resulting energy difference. The moment the two beams are at the required azimuthal position, the full beam is recaptured with a much higher RF voltage at the average (designed) RF frequency, creating a single batch of 48 bunches with half the bunch distance (50 ns).

Since slip-stacking can be tested experimentally only after the upgrade of the main 200 MHz RF system [3, 4], macro-particle simulations with the BLonD code [5] were carried out to design and optimise this manipulation [6]. The full SPS longitudinal impedance model was used together with realistic beam parameters (bunch lengths, intensities, particle distribution), based on beam measurements. The feasibility of slip-stacking was proven in the simulations and a first implementation scenario is currently underway [2]. However, loss of Landau damping was observed, starting at the moment of recapture and lasting until the end of the cycle. A detailed study of this effect, which can be attributed to the hollow longitudinal distribution, generated by the strongly unmatched conditions at the moment of recapture, is presented below. Possible ways to increase the longitudinal stability threshold are also proposed.

EFFECT OF RF PERTURBATION

During the slip-stacking process each batch will be captured by a different group of RF cavities. The group of cavities that is not synchronised with the batch will perturb its motion. This perturbation can be described by the slip-stacking parameter α [7]:

$$\alpha = \frac{\Delta f_{\mathrm{rf}}}{f_{s0}} = 2\frac{\Delta E}{H_{\mathrm{B}}}, \tag{1}$$

where Δf_{rf} and ΔE are respectively the differences in RF frequency and energy between the two batches and f_{s0} is the zero amplitude synchrotron frequency of the unperturbed bucket with half height of H_{B}.

When $\alpha = 4$, the separatrices of the buckets, associated with the two independent groups of RF cavities, are tangent to each other. This value was proven to be the lowest stability limit of the dynamics of the system [7], since the perturbation averages out within a synchrotron period. For lower values of α, the motion of the particles in the longitudinal phase-space becomes chaotic, leading to very fast particle losses. This implies that at the moment of recapture (end of MSS) the two beams should remain separated in energy. An example of the longitudinal phase-space of a bunch at the moment of recapture with $\alpha = 4.5$ is shown in Fig. 1. Note the very distorted particle trajectories in the longitudinal phase-space, even though $\alpha > 4$. Therefore, a high RF voltage $V_{\mathrm{rf}}^{\mathrm{rc}}$ at the center RF frequency is needed in order to capture as many particles as possible, which also causes a large emittance blow-up.

LOSS OF LANDAU DAMPING

A large number of macro-particle simulations were carried out in order to optimise the slip-stacking procedure [6]. Simulations started at 300 ZGeV/c assuming that all bunches

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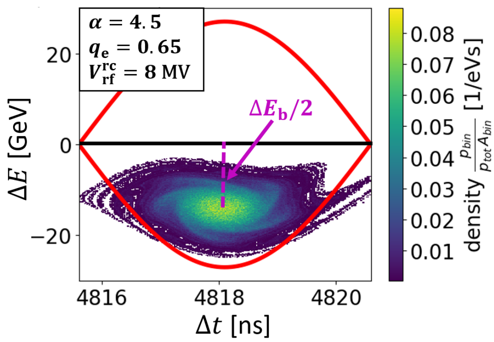

Figure 1: Example of the longitudinal phase-space of a bunch at the moment of recapture. The separatrix of the recapture RF voltage V_{rf}^{rc} is shown in red. The parameter q_e, constant during the MSS manipulation, corresponds to the filling factor of the bucket in energy.

of the two batches are stable and matched to the RF bucket with intensity effects. Since the slip-stacking manipulation results in unavoidable beam losses and longitudinal emittance blow-up, particular care was taken for the initial beam parameters to match the ones from beam measurements. This is important considering the large spread in bunch emittances and intensities that occurs during the long injection plateau (~40 s), due to the relatively strong effects of transverse space charge and intra-beam scattering [8]. An example of measurements performed in 2015 is shown in Fig. 2. One can see that the first bunches, which spend longer time at the flat-bottom, degrade more compared to the last ones, in terms of particle losses and longitudinal emittance reduction.

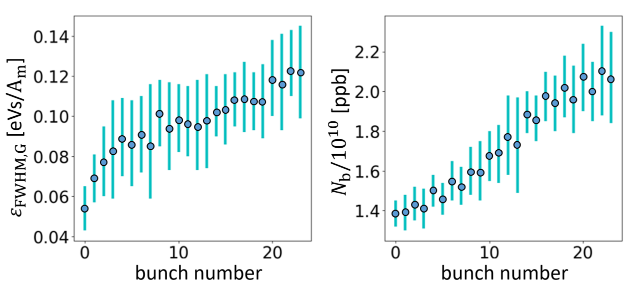

Figure 2: Measured longitudinal bunch emittance (left) and intensity (right) as a function of the bunch number at 300 ZGeV/c during the nominal LHC ion cycle of the SPS. The error bars indicate the standard deviation of the different sets of measurements [9]. The emittance ε is calculated from the measured 4σ bunch length, where σ is computed from the full-width-half-maximum of the bunch profile assuming a Gaussian distribution.

A binomial longitudinal particle distribution, $F(H) = F_0\,(1 - H/H_\tau)^\mu$, was chosen, where F_0 is a normalization factor and H_τ is the value of the Hamiltonian H along the trajectory enclosing all the particles. Here, a high value of $\mu = 5$ was used in order to take into account the long tails developed during the continuous particle loss at the flat-bottom.

As was shown in Fig. 1, at the moment of recapture the bunches are strongly unmatched to the RF bucket. Therefore, during filamentation, a hollow bunch in the longitudinal phase space is formed and this distribution is preserved until the end of the accelerating cycle. As a consequence, loss of Landau damping (LLD) is observed for the smaller and the least intense bunches, indicated by the strong dipole oscillations that continue until the end of the cycle [2]. Inspection of the phase-space distribution of one of these bunches shows a high density island that keeps oscillating around the bucket center (Fig. 3). Note that the voltage program for the ramp to the top energy was calculated for a constant filling factor q_e, based on the largest bunch after filamentation.

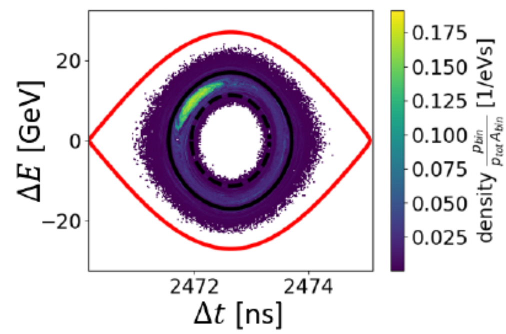

Figure 3: Example of the longitudinal phase-space of a bunch at the flat-top, for which LLD is observed, as indicated by the high-density island in the particle distribution.

An analytical calculation of the LLD threshold in intensity, for a constant reactive impedance $\mathrm{Im}Z/n$, can be found from the condition [10]:

$$N_b < \frac{\eta E}{q^2\beta^2}\frac{\tau}{\mathrm{Im}Z/n}\left(\frac{\Delta E}{E}\right)^2\frac{\Delta\omega_s}{\omega_s}, \qquad (2)$$

where q is the charge of the particle with velocity β (in units of c), η is the slippage factor, τ is the bunch length, $\Delta\omega_s/\omega_s$ and $\Delta E/E$ are respectively the relative angular synchrotron frequency and energy spreads. Calculations at the moment of recapture, assuming $\mathrm{Im}Z/n = 3\,\Omega$ [9], are in good agreement with the result obtained in simulations (Fig. 4). Similar agreement between these calculations and macroparticle simulations for the SPS flat-top was also presented in Ref. [9].

INCREASING THE LLD THRESHOLD

In the SPS, a forth harmonic RF system (800 MHz) is used in addition to the main one for the proton beams, in order to increase the synchrotron frequency spread of the particles inside the bunch and thus to enhance Landau damping [11]. This system was not used in operation with ion beams due to the relative small beam intensities (2-3×10^{10} charges per bunch). Thus, the obvious way to damp these persistent oscillations was to activate the 800 MHz RF system at flat-top, prior to extraction to the LHC. Although this would have been the easiest way to implement in the machine, the

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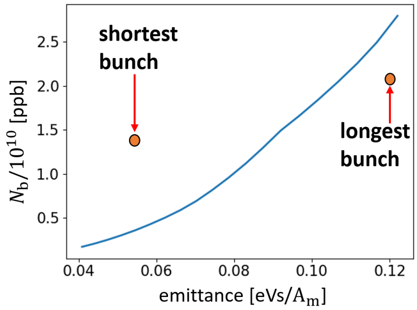

Figure 4: Analytical calculation of the LLD threshold in intensity versus measured emittance, at the moment of recapture with V_{rf} = 8 MV. The values for the shortest (ε_l = 0.054 eVs/A_m, N_b = 1.4×10^{10} ppb) and longest (ε_l = 0.122 eVs/A_m, N_b = 2.1×10^{10} ppb) bunches are marked by circles.

simulation results were not satisfactory: no damping was observed both for bunch shortening (BS) and lengthening (BL) modes for the available RF voltage. Note that the BS mode ($\Delta\phi = \pi$ between the 2 RF systems) with an RF voltage ratio of 0.1, is successfully used for the proton beams in the SPS, above transition energy, while in BL mode ($\Delta\phi = 0$) bunches become unstable [12].

This result can be explained by considering the synchrotron frequency distributions f_s of the particles within the bunch for the different operating modes. Figure 5 presents an example for the SPS flat-top (450 ZGeV/c) with V_{rf}^{200} = 5.5 MV. It is clear that, after adding the extra harmonic, no spread in f_s is obtained in the region occupied by the bunch, since the largest gain is in the bunch center, which in this case is empty.

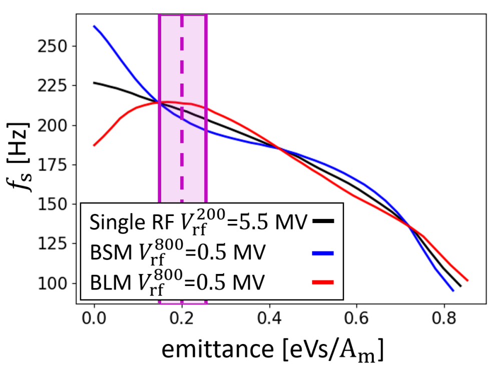

Figure 5: Synchrotron frequency distributions f_s versus longitudinal emittance, at the SPS flat-top. The magenta-colored region indicates the region that is occupied by the bunch.

Switching on the 800 MHz in BS mode at the moment of recapture, in order to increase the nonlinearities of the bunch before the hollow distribution is formed, was proven to be sufficient to completely damp the dipole oscillations of the shortest bunch. On the contrary, in BL mode even the large bunches became unstable (see Fig. 6).

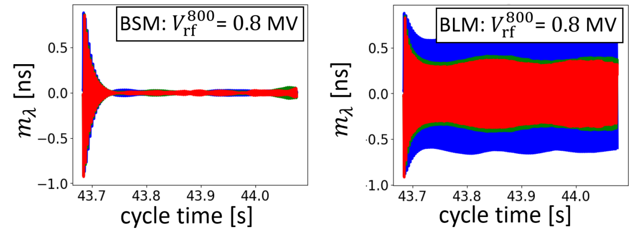

Figure 6: Dipole oscillations at 300 ZGeV/c (m_λ defines the average position of the bunch profile) of the first (blue, shortest) and last (red, largest) bunches in BS (left) and BL (right) modes. Simulations start after recapture (end of MSS). The 200 MHz RF voltage is 8 MV.

Examining again the f_s distribution (Fig. 7), one can see that in the BSM case, a considerable spread was introduced which can explain the damping of the oscillations, while in the BLM case, the bunch covers the region with $\mathrm{d}f_s/\mathrm{d}\varepsilon_l = 0$. This explains why the largest bunches became also unstable, since it has been proven that in these conditions, the LLD threshold decreases rapidly to zero [13, 14].

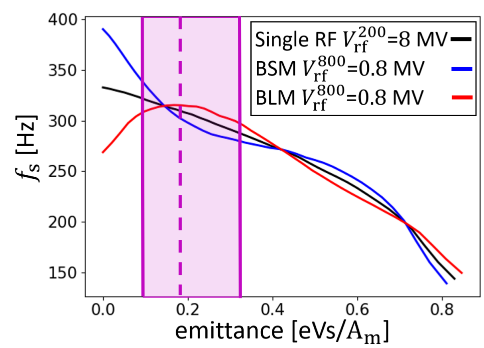

Figure 7: Synchrotron frequency distributions f_s versus longitudinal emittance, at the moment of recapture after MSS. The magenta-colored region indicates the region that is occupied by the bunch.

CONCLUSION

Momentum slip-stacking is planned to be used for the LHC ion beams in the SPS after LS2 to increase the total beam intensity required by the HL-LHC project. First implementation scenarios are based on realistic macro-particle simulations, since experimental tests can be done only after the upgrade of the 200 MHz RF system in 2021. However, loss of Landau damping was observed for the shortest bunches, due to the hollow longitudinal distribution generated at the end of the MSS manipulation. This led to un-damped oscillations of the bunch core, lasting until the end of the cycle. It was found that in order to damp these oscillations, the additional fourth harmonic RF system has to be applied in BS mode at the moment of recapture, while using it later in the cycle had practically no effect. BL mode made the bunches more unstable.

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