

# MOMENTUM SLIP-STACKING IN CERN SPS FOR THE ION BEAMS

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## Abstract

The LHC Injectors Upgrade (LIU) project at CERN aims at doubling the total intensity of the lead ion beam for the High-Luminosity (HL) LHC. Achieving this goal requires using momentum slip-stacking in the SPS, the LHC injector. Slip-stacking will be applied on an intermediate energy plateau to interleave two batches, reducing the bunch spacing from 100 ns to 50 ns and thus increasing the total number of bunches injected into the LHC. Realistic macro-particle simulations, with the present SPS impedance model are used to study and design this complicated beam manipulation. Slip-stacking can be tested experimentally only after the upgrade of the SPS 200 MHz RF system, in 2021. Preliminary, slip-stacking related beam measurements were performed at the end of 2018. In this paper both macro-particle simulations and beam measurements are reported with emphasis given on optimisation of the process, crucial to achieve the required HL-LHC parameters (bunch lengths, beam losses).

## INTRODUCTION

The LIU project at CERN [1] aims at doubling the total intensity of the Pb-ion beam to match the requirements of the HL-LHC project. In order to achieve that, momentum slip-stacking (MSS) is planned to be used in the SPS in 2021 [2], the first year after the Long Shutdown 2 (LS2).

This technique is being used already in operation at Fermilab [3]. It permits two high-energy particle beams of different momenta to slip azimuthally, relative to each other, in the same beam pipe. The two beams are captured by two RF systems with a small frequency difference between them. Each beam is synchronized with one RF system and it is perturbed by the other. The moment the two beams are stacked one on top of the other, the full beam is recaptured with a much higher RF voltage at the average RF frequency, allowing to double the bunch intensity at the end of the process.

A variant of this manipulation is considered in the SPS [1]: the two batches are not stacked on top of each other, but interleaved. In particular, two batches of 24 bunches, spaced by 100 ns, are going to be interleaved on an intermediate energy plateau to produce a single batch of 48 bunches with half the bunch distance (50 ns). The process is schematically illustrated in Fig. 1.

The MSS in the SPS is feasible thanks to the large bandwidth of the main 200 MHz RF system [4] (travelling-wave cavities, TWC) and the undergoing power and low-level RF (LLRF) upgrades [5, 6]. During LS2, each cavity will be equipped with individual cavity and beam controllers, essential for the MSS. Therefore, since independent LLRF controls will be available only after 2021, longitudinal macro-

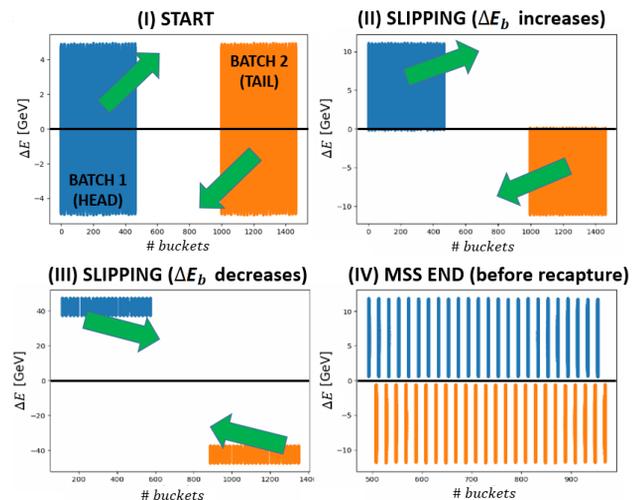


Figure 1: Illustration of the MSS procedure as planned in the SPS. The two batches, starting from Phase I, move in longitudinal phase space relative to each other. The black line marks  $\Delta E = E - E_0 = 0$ , where  $E_0$  is the design energy. In Phase II the distance in energy  $\Delta E_b$  between the batches increases, while the opposite happens in Phase III. Recapture is done in Phase IV.

particle simulations are the only way to verify the MSS feasibility.

Realistic macro-particle simulations using the BLonD code [7], including the detailed SPS longitudinal impedance model and measured beam parameters, have been carried out in 2018 in order to design and optimise the slip-stacking process [8]. This paper summarizes the latest results of this study, defining the operational slip stacking scenario for 2021. Furthermore, some preliminary (relevant to the MSS) measurements of the LHC Pb-ion beam in the SPS, which took place at the end of 2018, are presented.

## IMPLEMENTATION SCENARIO

The LHC Pb<sup>82+</sup> ion beams in the SPS are currently accelerated from 17 ZGeV/c ( $\gamma=7$ ) to 450 ZGeV/c ( $\gamma=191$ ). For the available SPS optics configurations (Q20, Q26), transition energy is crossed early in the cycle ( $\gamma \sim 20$ ). Since a constant magnetic field is required for the MSS manipulation, an intermediate energy plateau of  $\sim 1$  s was added at 300 ZGeV/c ( $\gamma=127$ ) in the cycle, well above the transition energy. This decision is supported by the fact that at the long injection plateau ( $\sim 40$  s), considerable beam degradation occurs, due to the relatively strong transverse space charge and intra-beam scattering [9]. Furthermore, simplified scaling laws show that all the relevant to slip-stacking parameters favor higher energies [10]. On the other hand, at the top

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energy the bunches are more prone to longitudinal instabilities [11] and in addition, the un-captured beam that is generated during the MSS, would be transferred to the LHC. This can be avoided if MSS is performed at an intermediate energy.

As mentioned above, during the MSS process each batch will be controlled by a different group of RF cavities. The group of cavities that is not synchronised with the batch can perturb its motion. This perturbation can be described by the slip-stacking parameter [12],  $\alpha = \Delta f_{rf}/f_{s0} = 2\Delta E/H_B$ , where  $\Delta f_{rf}$  and  $\Delta E$  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 buckets of the two RF systems are tangent to each other, which corresponds to the lowest stability limit. For lower values of  $\alpha$ , the motion of the particles in the longitudinal phase-space becomes chaotic. This implies that at the moment of recapture (end of MSS) the two beams should remain separated in energy (see plot IV in Fig. 1). Thus, high RF voltage at the center frequency is needed in order to capture all the particles, causing a large emittance blow-up at the end of the process.

The aforementioned limitation becomes very important in the beginning of the manipulation, when the separation of the two batches starts. For this reason, amplitude modulation on the two groups of RF cavities will be applied during MSS, meaning that only one group should be active when the corresponding batch passes by. To ensure that this requirement is fulfilled and taking also into account the filling time  $\tau_f$  of the cavities, a certain initial distance between the two batches  $T_B$  is introduced. In simulations,  $\tau_f = 1 \mu s$  was assumed (4 section cavity) [13], while a relatively large  $T_B = 2.7 \mu s$  was introduced, to ensure the adiabaticity of the process.

A large number of macro-particle simulations were carried out in order to optimise the MSS procedure for the two available optics [8]. Simulations started at 300 ZGeV/c, assuming that all the bunches of the two batches are stable and matched to the RF bucket, including intensity effects (the SPS impedance model was used). The initial large spread of the beam parameters in terms of intensity and bunch lengths (emittances) as well as a realistic bunch distribution were taken into account using beam measurements of 2015 [14]. The momentum (frequency) and RF voltage programs needed for the MSS manipulation have been calculated using two iterative algorithms, developed in order to ensure the correct alignment of the two batches at the moment of recapture. Both algorithms treat independently the two RF systems assuming no interaction between them, while for the calculations, constant longitudinal emittance  $\varepsilon_l$  (defined by the largest bunch within the batch) and filling factor in energy  $q_e$  were used. Restrictions with respect to the machine momentum aperture and the bandwidth of the RF cavities were also taken into account. An example of the RF programs used in simulations, for one group of cavities, is presented in Fig. 2. Similar programs were used for the

second group of cavities (identical in voltage and symmetric in momentum with respect to the design value  $p_0$ ).

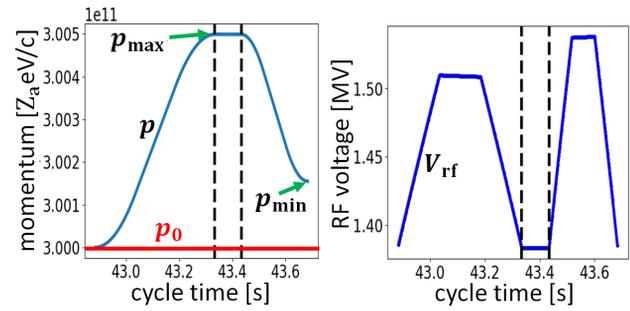


Figure 2: Example of momentum (left) and RF voltage amplitude (right) programs used during the MSS simulations, for one group of cavities.

Three parameters were scanned in the optimisation process:  $q_e$  during MSS,  $\alpha$  and  $V_{rf}$  at the moment of recapture. Furthermore, adiabatic bunch compression as well as bunch rotation were considered at flat-top as a possible RF manipulation, prior to extraction to the LHC. The optimisation was based on two goals: 1) minimizing the total beam losses  $L_{tot}$  and 2) minimizing the longitudinal emittance blow up after recapture. The latter is imposed by the fact that the average bunch length at the SPS extraction  $\tau_{avg}$  should not exceed 1.65 ns, otherwise beam losses in the LHC can exceed the acceptable limits (capture by a 400 MHz RF system). Summary plots of the possible solutions in the Q26 ( $\gamma_{tr}=22.83$ ) and the Q20 ( $\gamma_{tr}=18$ ) optics, assuming adiabatic bunch compression at flat-top, are shown in Fig. 3.

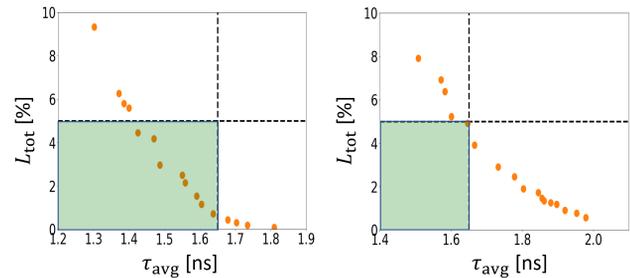


Figure 3: Possible solutions in the  $L_{tot}-\tau_{avg}$  plane found from simulations in the Q26 (left) and Q20 (right) optics with bunch compression at flat top. The area where the constraints are satisfied is shown in green.

One can clearly see that for the Q20 optics (used in recent operation for ions and protons) no acceptable solution was obtained, due to the lower  $\gamma_{tr}$ . Note that 15 MV as the maximum available RF voltage were assumed [5]. Instead, bunch rotation is needed in order to achieve sufficiently short bunches at extraction, adding an additional complication into operation. Therefore, the Q26 optics, providing more margin to the final beam parameters, was selected for the MSS cycle. As a result, the Q26 optics became operational for the ion beams already in 2018 without any impact on the achieved beam parameters compared to the previous years [15].

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At the moment of recapture (high RF voltage at the designed frequency), loss of Landau damping was observed in simulations for the shortest bunches in the batch. This effect is enhanced by the strongly unmatched bunch, which is displaced in energy relative to the bucket centre ( $\alpha \geq 4$ ). During filamentation, a hole in the longitudinal phase-space is formed and for the shortest bunches, strong dipole oscillations are observed until the end of the cycle (Fig. 4). A strong density island in the phase-space distribution of the shortest bunch is still preserved at the flat-top. Note that the voltage program for the ramp to the top energy that was used in simulations was also calculated for a constant  $q_e$ , based on the largest bunch after filamentation.

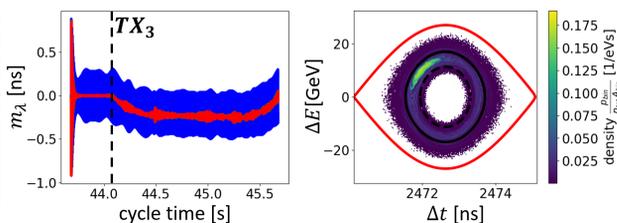


Figure 4: Example of simulations for one acceptable scenario in the Q20 optics. Left: dipole oscillations along the cycle after MSS, for the first (blue, shortest) and last (red, longest) bunches.  $m_\lambda$  defines the average position of the bunch profile. The vertical line indicates when the ramp to the top energy starts. Right: longitudinal phase-space distribution of the shortest bunch at flat-top.

In the SPS, a fourth harmonic RF system (800 MHz) is used in addition to the main one to enhance Landau damping for the proton beams [16]. This system was not used in operation with ion beams due to the relative small beam intensities ( $2-3 \times 10^{10}$  charges per bunch). However, simulations have shown that in order to damp the dipole oscillations after MSS, the 800 MHz RF system should be applied from the moment of recapture until the end of the cycle [17].

## MEASUREMENTS

A successful implementation of slip-stacking relies on beam stability and reproducibility all along the cycle. Measurements of the LHC ion beams, carried out in 2018, have shown that longitudinal instability occurs after transition crossing. The beam could be stabilized by a deliberate degradation of the transition crossing, causing a strong emittance blow-up (see left plot in Fig. 5). For the MSS two main difficulties arise from this behaviour: 1) the enhanced bunch by bunch parameter variation within the batch, which is already generated at the long flat bottom and 2) the uncontrolled occurrence of this blow-up, resulting in a non reproducibility from cycle to cycle.

Attempts to optimise transition crossing in order to control the blow-up, shifted the beam instabilities later in the cycle. This is illustrated on the right plot in Fig. 5, where measurements of the MSS cycle, used in machine development (MD) studies, are shown.

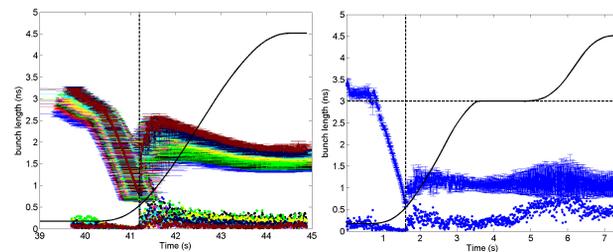


Figure 5: Average bunch length evolution along the cycle. Left: nominal LHC ion cycle. Different colours correspond to the different batches. Right: slip-stacking cycle used in MDs. The dots on the bottom show the bunch length spread within each batch. The black solid lines correspond to the momentum cycle (17 - 450 ZGeV/c), while the vertical lines indicate the transition crossing.

The longitudinal instability threshold can be significantly increased by using the 800 MHz RF system. The observed instabilities all along the cycle, as well as the need in an efficient control of the beam parameters imposed by slip-stacking, make it essential for the future operation. However, due to the cavity bandwidth, its use is possible only after transition crossing. In addition, the possibility of applying Controlled Emittance Blow-up (CEBU) during the cycle to increase the instability threshold is also considered (it is routinely used for the proton beams). CEBU could be used, for example, before transition crossing, where bunches become very small ( $\tau \sim 0.5$  ns), as it is shown in Fig 5.

## CONCLUSION

Momentum slip-stacking is planned to be used for the LHC ion beams in the SPS after LS2 to reduce the bunch spacing from 100 ns to 50 ns and thus to increase the total beam intensity for the HL-LHC project. A first implementation scenario of the MSS manipulations, based on realistic macro-particle simulations, was presented. This can be tested experimentally only after the upgrade of the 200 MHz RF system in 2021. However, the longitudinal instabilities observed in beam measurements after transition crossing, together with the loss of Landau damping found in simulations for the shortest bunches, make its implementation very challenging. Means to increase the instability threshold are being considered, including the use of the additional 800 MHz RF system along the cycle as well as applying CEBU before transition crossing.

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