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INVESTIGATIONS OF LOSSES ON THE CERN SPS FLAT BOTTOM WITH HL-LHC TYPE BEAMS

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Abstract

The High-Luminosity LHC (HL-LHC) project at CERN aims at doubling the beam intensity and the brightness. To achieve this unprecedented performance, the LHC injectors were upgraded during the Long Shutdown 2 (2019-2021) to overcome limitations such as space charge and beam instabilities. Despite these upgrades, the reduction of beam loss on the flat bottom in the Super Proton Synchrotron (SPS) to reach the target beam parameters remains a challenge, avoiding unnecessary activation. Losses are due to several factors: uncaptured beam in the SPS due to the bunch rotation in the Proton Synchrotron (PS) prior to the transfer, large transient beam loading during multiple SPS injections, and transverse tails reaching aperture limitations. Investigations were conducted with HL-LHC beam parameters, aiming at disentangling the different sources of losses and defining specific observables. Finally, refining the optimal beam parameters for improved transfer between PS and SPS is the objective of the study, as well as the possible need for new hardware such as an additional RF system for beam stability and capture or a dedicated collimation system.

INTRODUCTION

The beam for the Large Hadron Collider (LHC) is produced by a chain of injectors accelerating it up to an energy of 450 GeV. Along this chain, one critical step is the transfer of the beam from the PS to the SPS at an energy of 26 GeV. The bunch-to-bucket transfer hands the beam from an RF system in the PS at 40 MHz (RF harmonic $h = 84$) over to the one in the SPS at 200 MHz ($h = 4620$).

To fit the bunch longitudinally into the five times shorter RF bucket of the SPS, a non-adiabatic bunch shortening is performed by applying a step increase of RF voltage in the PS [1]. For the nominal longitudinal emittance of 0.35 eVs, this reduces the bunch length from 16 ns to 4 ns. Not all particles may be captured in the SPS RF bucket due to the nonlinear synchrotron motion of particles at large amplitudes [2]. Uncaptured particles keep circulating in the ring and are usually lost at start of acceleration when they are separated from the captured beam in the longitudinal phase space.

After capture, the beam is kept in the SPS at constant energy (injection energy, referred to as flat-bottom) for a multiple of 3.6 s. This corresponds to the time necessary for the PS to accelerate and inject new batches to fill the SPS. Two main loss mechanisms are observed at low energy in the SPS: First, losses then happen rapidly right after injection (50 ms, about 50 periods of the synchrotron frequency), and then slowly on the flat bottom. The origin of the slow losses is usually more difficult to establish as it could arise from many sources: tune and chromaticity settings, scraping of tails, collective effects, large orbit excursion and loss of particles at large momentum offset.

The losses described above can be measured using a DC Beam Current Transformer (BCT) measuring the beam current circulating in the ring (bunched or coasting). A typical intensity versus time is shown in Fig. 1.

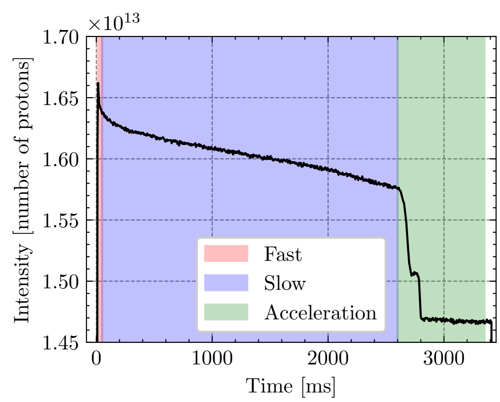

Figure 1: Overview of the losses as measured by a DC BCT in the SPS (cycle with short flat-bottom, single injection). Fast beam loss occur right at capture (red, 50 ms), slowly on flat-bottom (blue), and at start of acceleration (green).

During the 2019-20 Long Shutdown (LS2), the LHC injector chain was upgraded to achieve the beam parameters for the HL-LHC project [3, 4]. The key objectives were to increase the intensity by a factor of two, while reducing the transverse emittance and keeping the longitudinal emittance constant. An additional requirement is to maintain the losses in the SPS below the target of 10 % to limit the activation of the accelerator and avoid compensating with an increased beam intensity from the pre-injectors. Losses in the SPS were studied thoroughly before the injector upgrades through measurements and simulations, predicting that the 10 % budget should be difficult to achieve but within reach [5–7]. In this contribution, we describe the operational experience in terms of losses at flat bottom for HL-LHC beams in the SPS, as well as investigations of the loss mechanisms.

BEAM PERFORMANCE IN 2022

Different beam variants for the LHC can be produced from the PS with a bunch spacing of 25 ns. The "Nominal" scheme [8] consists of trains of 72 bunches, while

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the "BCMS" [9] is a higher-brightness variant composed of 48 bunches, and the 8b4e is a special case with 8 bunches and 4 empty buckets to mitigate electron cloud. From one to five injections can be made from the PS to the SPS depending on the beam variant, more details can be found in [10]. A summary of the best achieved performance for these beams in terms of total losses from PS extraction to after start of acceleration in SPS is presented in Fig. 2, accumulating data of the entire 2022 run.

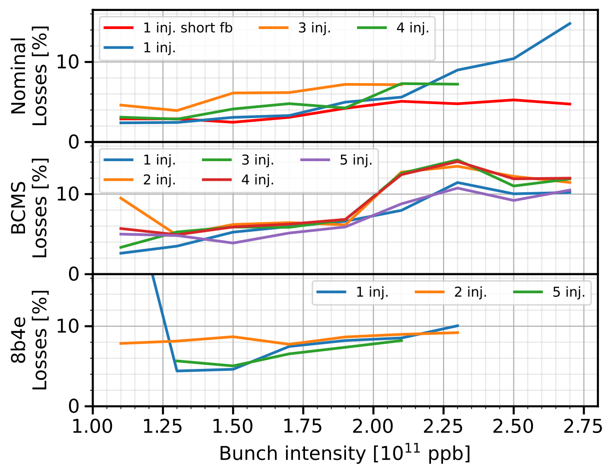

Figure 2: Summary of measured total losses in the SPS in 2022 for the Nominal (top), BCMS (middle), 8b4e (bottom) beam variants and for variable number of injections. The red line correspond to a test cycle with a short time flat bottom during a Machine Development (MD) study.

Many important milestones were reached in 2022 in the SPS. The year was marked by the first consistent and stable injection of the beam intensity for HL-LHC into the SPS (2.6×10^{11} protons per bunch, ppb), during Machine Development (MD) sessions. Another important milestone was that the best performance for the BCMS beam with 5 injections in the SPS is below the 10% loss limit. Note that this does not include other sources of losses during the ramp, 3-5% tail scraping is usually required for transfer to the LHC and should be accounted for in the loss budget. For this performance, the distribution is: fast 2.9%, slow 5.3%, acceleration 1.6%. The overall losses remained high and the best achievable transmission was difficult to reproduce along the year, requiring continuous tuning especially at higher beam intensities.

Investigations were continued to better understand the root cause of these losses. A first step was to measure the dependency of the losses as a function of the beam intensity for the dedicated study cycle (Nominal LHC beam on a short flat-bottom) and is presented in Fig. 3. The first observation is the dependency of total losses as a function of intensity, pointing towards potential collective effects or aperture limitations reached due to the increasing transverse emittance.

The dependency of the losses at start of acceleration is less evident than the fast and slow losses which are linear with

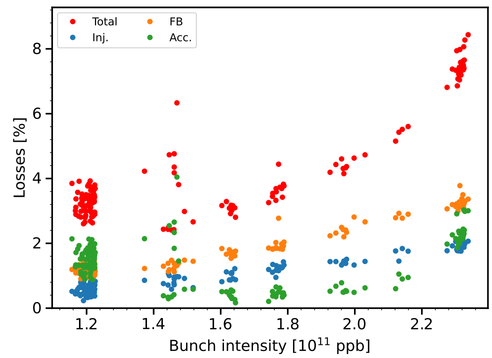

Figure 3: Losses as a function of beam intensity for the MD cycle decomposed according to the definitions from Fig. 1.

intensity. Acceleration losses are expected to correspond to the uncaptured beam circulating in the ring. One can notice the larger losses at 1.2×10^{11} ppb in Fig. 3, which were found to be due to a poor adjustment of the RF phase at injection during setting-up. It also appears that the losses at start of acceleration suddenly increase at 2.2×10^{11} ppb, which were analyzed in detail in the longitudinal plane.

LONGITUDINALLY UNCAPTURED BEAM

The longitudinal capture of the PS bunches in the SPS RF buckets requires fine adjustments in both accelerators. Longitudinal observations at injection were done to investigate the source of the losses put in evidence in Fig. 3.

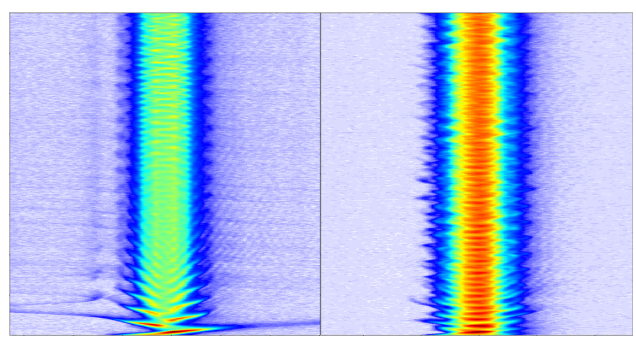

Figure 4: Measured bunch oscillations at injection in the SPS at 2.6×10^{11} ppb for the first (left) and the last (right) bunch of a 72 bunch train injected in the SPS. In abscissa is the time coordinate of the bunch and in ordinate the acquisition frames (one frame acquisition per revolution period).

The measurements are done with a wide-band pick-up [11] acquiring the longitudinal profiles of the bunch train during each turn for the first 2000 turns (≈ 46 ms). An example of the measured beam oscillations at SPS injection is shown in Fig. 4, comparing the first and last bunches of the batch. Each horizontal line in Fig. 4 corresponds to one acquired trace, stacked vertically displaying the synchrotron oscillations of the bunches. Starting from the last (Fig. 4, right), the main observation is that the bunch performs quadrupolar oscillations. These are expected as the SPS RF voltage is intentionally larger than the one from the matching condition

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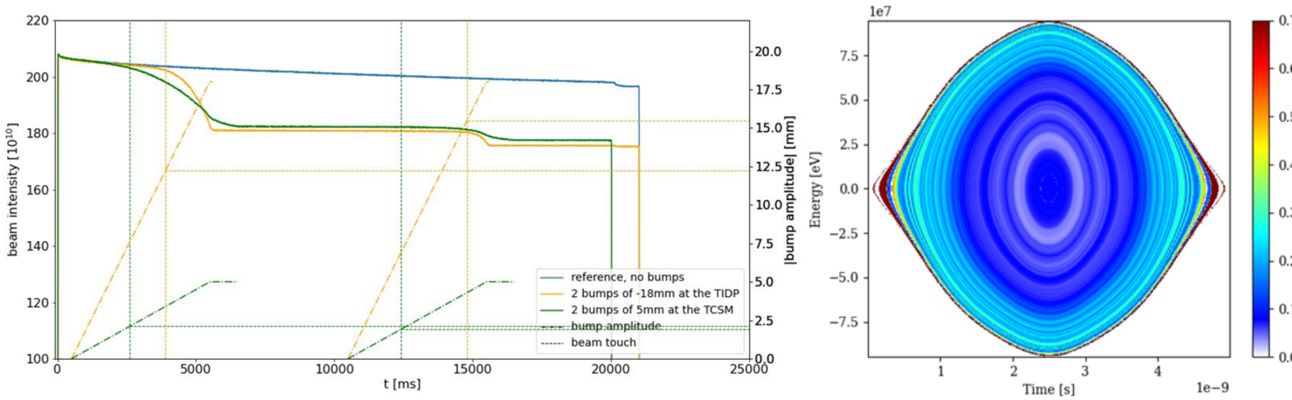

Figure 5: Observations during horizontal and vertical tail scraping on the SPS flat bottom. Left: Beam intensity measured on a long flat bottom with horizontal scraping together with the evolution of the beam orbit and the estimated amplitude of the reached aperture. Right: Longitudinal phase space reconstruction of the relative beam loss in the RF bucket comparing before/after vertical scraping.

to capture more particles [5]. More importantly, the first bunch undergoes strong phase oscillations causing particles to leave the RF bucket on both sides and coinciding with the increased losses above 2.2×10^{11} ppb. Due to the strong transient beam loading at SPS injection, the first bunches in the train are not aligned in phase to the RF bucket. Note that the bunch spacing in the PS is more regular as the ring is almost full, reducing transient beam loading effects. New digital implementation of cavity feedback systems are now included in the SPS to mitigate transient beam loading [12]. Further studies will be required for adjustments at highest beam intensity.

Another test performed in 2022 was to apply controlled longitudinal emittance blow-up on the flat-bottom. The approach was to push particles out of the RF buckets in order to better put in evidence the contribution of the uncaptured beam to the loss distribution along the cycle. A preliminary study showed that increasing the uncaptured beam population up to 20% of the total intensity was not contributing to the slow losses but only to the ones at start of acceleration measured by the DC BCT.

TRANSVERSE TAIL SCRAPING

Investigation of sources of slow losses by scraping tails in the transverse plane was of equal importance. Tests in 2022 were started in the horizontal plane, where a collimation system was already considered to mitigate impact of losses from dispersive contributions [13]. Scraping could be done by applying an orbit bump on intercepting devices, either in high or low dispersion regions (respectively at TIDP for momentum scraping and TCSM, an LHC-type collimator). An example is presented in Fig. 5 (a). In both cases, a complete removal of the tails stopped the slow losses. A thorough evaluation is now needed to distinguish the relative contribution of the dispersive and betatronic components of the horizontal profile. Another observation is that applying a second orbit bump of the same amplitude leads to further losses possibly indicating a repopulation of the tails. The mechanism behind such tail repopulation remains to be established.

Scraping was also performed in the vertical plane. Like in the horizontal plane, slow losses vanish after the removal of vertical tails. No coupling is expected in first order between horizontal and vertical planes in the SPS. With this constraint, a possible explanation would be that particles at large betatronic oscillation amplitudes in both transverse planes are correlated, presumably already from the pre-injectors. Interestingly, vertical tail scraping led to a reduction of the bunch length, in the longitudinal plane. Note that no dispersion in the vertical plane is expected in the SPS. This was verified by subtracting the reconstructed longitudinal phase space distribution before and after vertical scraping. As seen in Fig. 5 (b), the relative loss is indeed more important at large amplitudes in the RF bucket. This correlation is also suspected to originate from the SPS pre-injectors.

Overall, the scraping measurements indicate a possible correlation in the distribution of particles at large betatron and synchrotron amplitudes in all three planes, which significantly complicates the effort to disentangle the root cause of losses in the SPS.

CONCLUSIONS

The beam performance reached in 2022, although promising, showed that losses are still substantial on the SPS flat-bottom. The present observations confirm that uncaptured beam in the RF bucket will be lost at the start of acceleration and is dependent on transients at PS-SPS transfer. Regarding slow losses, tail scraping either in the horizontal or vertical plane shows a clear reduction of the slow loss rate. The tail population is presently being carefully investigated across the injector complex [14]. A potential correlation in the particle distribution in all three planes was observed. This will be an important consideration for further investigations in 2023.

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