ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPB030

CHARACTERISATION OF TRANSVERSE PROTON BEAM LOSSES AT THE CERN SUPER PROTON SYNCHROTRON

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Abstract

The High-Luminosity LHC (HL-LHC) project foresees nearly doubling the design beam intensity of CERN's Large Hadron Collider (LHC). A particularly pressing issue is the observation of significant beam losses at the flat bottom in the Super Proton Synchrotron (SPS) that delivers these beams to the LHC. These losses arise from multiple factors: uncaptured beam losses that are generated during the bunch rotation in the Proton Synchrotron (PS) before the transfer to the SPS; large transient beam loading effects in the RF system during multi-turn SPS injections; and the diffusion of over-populated transverse tails, which reach aperture limitations. Dedicated beam measurements were carried out in the SPS as a first step towards untangling these losses. These studies aimed to disentangle the various loss mechanisms, with a focus on the halo population and potential correlations between transverse and off-momentum tails.

INTRODUCTION

The CERN Super Proton Synchrotron (SPS) is the final accelerator in the injector chain of the Large Hadron Collider (LHC) and plays a crucial role in delivering high-quality beams at 450 GeV to the LHC. In the framework of the High-Luminosity LHC (HL-LHC) project [1], the SPS was upgraded within the LHC Injectors Upgrade (LIU) project and must now accelerate beams with significantly higher intensity–up to $2.6 \cdot 10^{11}$ protons per bunch–while maintaining beam losses below a 10 % threshold [2]. Staying within this budget is essential to avoid excessive activation and operational downtime, and to ensure efficient transfer of the high-intensity beam to the LHC, without overburdening the upstream accelerators [3].

Losses in the SPS are observed predominantly at three critical stages: in the first 50 ms immediately following injection (about 50 synchrotron periods), during the long injection energy plateau, and at the start of the acceleration ramp. Among these, the losses on the flat bottom are particularly complex, arising from a combination of mechanisms [4, 5]. These include incomplete longitudinal capture of the beam transferred from the Proton Synchrotron (PS) [6, 7], injection transients related to beam loading in the RF systems, and continuous diffusion of particles in the transverse tails[4].

Previous studies have investigated these effects through simulations and measurements [8–10]. They suggest that, especially with HL-LHC-type beams, the loss budget risks being exceeded. The concept of a dedicated collimation system in the SPS has been studied to intercept and safely remove beam halo and uncaptured particles in well-defined locations [11, 12]. Its future deployment is subject to a confirmation that losses represent a problem, that such a system would be an effective solution, and that no other mitigations can be found, which is being assessed.

This paper presents the first steps towards a detailed characterisation of the beam losses observed at the SPS flat bottom for HL-LHC-type beams. Dedicated measurements have been carried out to better understand the role of the tail population, the evolution of losses in time, and potential correlations with longitudinal losses. The findings support the need to reassess current loss mitigation strategies and lay the groundwork for designing a potential collimation system to manage these losses more effectively.

RELEVANT SPS HARDWARE FOR COLLIMATION STUDIES

Several intercepting devices are installed in the SPS (see Fig. 1), which, while not designed as a complete collimation system, play a significant role in current beam loss studies. The hardware most relevant for collimation studies includes a prototype horizontal collimator [13], an off-momentum absorber block, and several vertical intercepting devices.

Horizontal Collimator Prototype

The SPS hosts a single horizontal betatron collimator, the TCSM.51932, originally installed as a prototype for the development and testing of LHC collimator control systems [13]. It was then replaced with a more advanced prototype that features in-jaw BPMs [14]. The device features a hollowed-out internal structure, which limits the total beam intensity it can safely intercept to around 72 bunches of

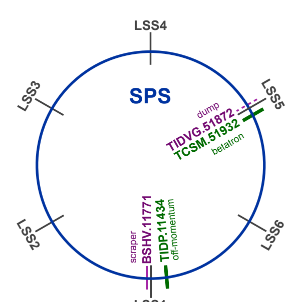

Figure 1: Position of relevant beam-intercepting devices in the SPS. LSS1 is the injection section.

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Table 1: Modelled Optics at the Intercepting Devices

	β_x [m]	$\sigma_{3.5\,\mu\mathrm{m}}$ [mm]	$\sigma_{2\,\mu\mathrm{m}}$ [mm]	D_x [m]	1 bucket excursion [mm]
TCSM.51932	33.755	2.067	1.563	-0.427	-1.643
TIDP.11434	94.093	3.452	2.609	2.899	11.162

$1.1 \cdot 10^{11}$ protons at injection energy. Due to this limitation, it is not suited for use during standard LHC-type cycles.

Operationally, the collimator must be fully retracted (±31 mm from the beam axis) before injection of LHC-type beams. However, with a maximum movement speed of approximately 1.5 mm/s, there is insufficient time to move the jaws in and out during a single SPS cycle. As a result, using the TCSM in collimation studies requires operating in COAST mode, which effectively stitches together multiple cycles to provide an extended time at constant energy. This mode of operation is subject to specific limitations, such as a 100 ms dead time in the beam loss monitor (BLM) acquisition at every repeated cycle, which constrains the usable beam intensity as the machine is not protected by the regular BLM interlocks during this dead time. For this reason, collimation studies with the TCSM are typically performed with a reduced beam of 12 nominal LHC-type bunches.

Off-Momentum Absorber Block

To intercept particles with large off-momentum, the SPS features an absorber block, called TIDP.11434, situated in a region of high horizontal dispersion. Under standard conditions, its horizontal aperture of 146 mm can be shifted such that the beam sees a physical boundary ranging from −40 mm to +105 mm relative to the nominal beam position. This asymmetric positioning is chosen to intercept halo particles with negative relative momentum offsets ($\delta < 0$).

Since the device's mechanical adjustment is relatively slow, the TIDP position is typically kept fixed, and when operational flexibility is needed, as for dedicated studies, defining a target momentum cut is achieved by applying a local orbit bump. This technique enables controlled interaction with the block, providing beam transverse displacements of up to 30 mm at 26 GeV. This strategy is only effective at relatively low energies, as the bump is limited by the corrector strength at larger energies.

Vertical Intercepting Devices

The SPS is also equipped with vertical scraping devices, primarily the BSHV.11771 which is routinely used in operation. In addition, a new vertical dump block, TIDVG.51872, additionally functions to intercept the vertical halo continuously. For the present study, however, the vertical intercepting devices were kept away from the beam and are not considered further in this paper.

MEASUREMENT RESULTS

To better understand the losses at flat bottom, dedicated measurements were performed during a dedicated machine development session (19 June 2024). These were done at injection energy, with 12 high-intensity bunches of $2.4 \cdot 10^{11}$ protons each, using the nominal optics for LHC-type beams (Q20). Relevant optical functions at the TCSM and TIDP are listed in Tab. 1. Several COASTs were performed, each lasting up to 45 minutes, allowing the TCSM collimator to move to any desired position.

Off-Momentum Scraping

To quantify the off-momentum population of the uncaptured beam (particles out of the bucket), scraping was per-

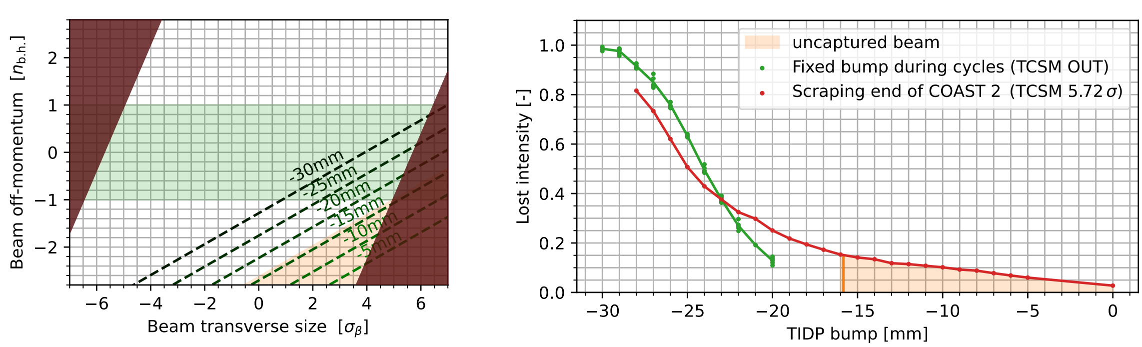

Figure 2: Off-momentum scraping with the TIDP. Left: Representation of the intensity cut by the TCSM (dark red), captured beam in the longitudinal bucket (green), and scraping as a function of the orbit bumps towards the TIDP (dashed green). At small bump amplitudes, only the uncaptured beam is intercepted (orange). The horizontal axis represents the horizontal position expressed in beam size (with a normalised emittance of 3.5 μm), and the vertical axis the off-momentum variable δ expressed in bucket height. Right: Measured intensity loss per bump amplitude during scraping (red) and over cycles (green). Due to time constraints, the latter was performed only for larger bumps.

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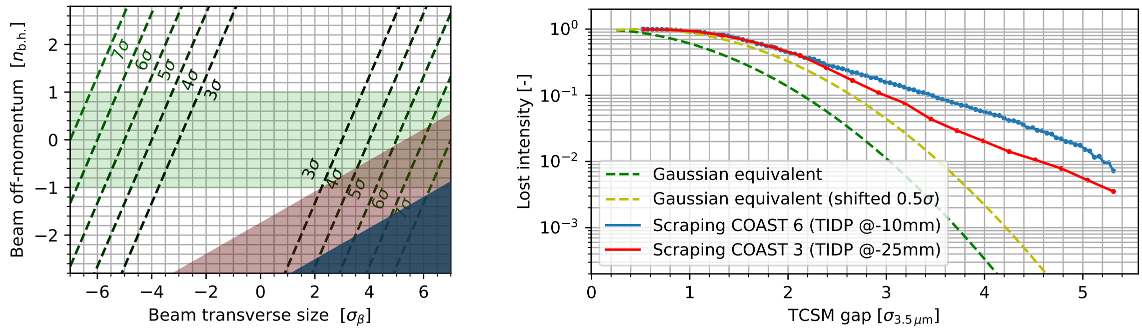

Figure 3: Betatronic scraping with the TCSM. Left: Intensity cut by the TIDP with an orbit bump of −10 mm (dark blue) and −25 mm (red), and scraping jaw positions of the TCSM (dashed green). Right: Measurement of the lost intensity for a given TCSM jaw position with the orbit bumps at −10 mm (blue) and at −25 mm (red) around the TIDP. Also shown is the expected population of an equivalent 2D Gaussian, centred around $0\,\sigma$ (dashed green) and around $0.46\,\sigma$ (dashed yellow).

formed. This is illustrated on the left of Fig. 2, where the horizontal axis represents the horizontal beam coordinate in beam size units, and the vertical axis represents the longitudinal beam coordinate expressed in units of bucket height. At injection, the latter is equal to 94.4 MeV (or $\delta = 3.642\cdot10^{-3}$). The TCSM is kept at a fixed position of $5.7\,\sigma$, and the beam is brought towards the TIDP using orbit bumps in steps of 1 mm. The green region represents the RF bucket, and the dark red the beam that is cut away by the TCSM. The dashed lines represent the relative position of the TIDP for different orbit bumps. Note that for small bumps, the part that is scraped away is purely uncaptured beam (orange region), as any in-bucket protons that would reach the TIDP are intercepted by the TCSM first.

The results are shown in the right plot of Fig. 2, red line. Note that the fraction of uncaptured beam is much larger than normally expected (0.5 % for a single batch of 72 bunches [4]). As the scraping was performed at the end of the COAST, on a beam that was stored in the ring for more than 15 minutes, one possible explanation is that slow diffusion processes have pushed previously captured beam out of the bucket. Indeed, in another test with regular cycles (without COAST), where the TIDP bump is applied 10 s after injection (Fig. 2-right green line), the core population seems much more in line with prior observations [4, 5].

Betatron Scraping

Similarly, the betatron population of the transverse tails is investigated by a TCSM scraping measurement from $5\,\sigma$ to $0.5\,\sigma$, in steps of 550 μm (with a −25 mm orbit bump around the TIDP) or 100 μm (with a −10 mm orbit bump around the TIDP), see Fig. 3. First of all, note that the red and blue plots look shifted w.r.t the core of a Gaussian equivalent. This is not yet fully understood and is still under investigation, but it might be due to a misalignment of the collimator or an orbit shift. Furthermore, comparing the measurement with the TIDP deeply in (red line) to the one with the TIDP further out (blue line) clearly shows that the off-momentum content strongly contributes to the betatronic tails, confirming our suspicions that they are correlated. A disentanglement of these will prove to be crucial for our future understanding of the losses. Finally, in both cases, the tails are strongly overpopulated w.r.t. their Gaussian equivalent. Though the origin of this overpopulation is not yet fully understood, it is in line with recent halo measurements on these beams after their injection into the LHC [15].

CONCLUSIONS AND OUTLOOK

Multiple observations have been made during the measurements. First of all, the betatronic tails are much more populated than the Gaussian equivalent. This observation is also seen at the LHC, and future studies will focus on exploring correlations between measurements in the two machines. These measurements suggest that a purely off-momentum collimation system, as proposed in [11, 12], might not be a fully efficient solution to remove the beam halo. Furthermore, there is a clear correlation between the betatronic and off-momentum tail populations. This correlation seems to result from a slow diffusion process that pushes particles out of the bucket, however, it is observed for long timescales and may not be relevant for operational LHC cycles.

We plan to extend these measurements in the future, focusing on a more robust alignment of the TCSM and smaller steps during scraping with more relaxation time in between to increase precision. Finally, we will perform multiple COASTs at different energies to clean the uncaptured beam and study the off-momentum diffusion, as well as perform tests on the nominal cycle used for LHC beam acceleration, as well as study the feasibility of orbit bumps in operation.

ACKNOWLEDGEMENTS

This research was funded in part by the National Science Centre, Poland, project number: 2021/43/D/ST2/02761. The authors would furthermore like to thank the SPS operation team, the MD coordination, as well as K. Li, H. Bartosik, and G. Rumolo for their help and invigorating discussions.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPB030

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