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OPERATIONAL DEPLOYMENT OF HIGH BRIGHTNESS LHC BEAMS IN THE SPS

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Abstract

Following the LHC Injectors Upgrade (LIU) programme, there has been a gradual ramp-up of the intensity of LHC beams in the CERN Super Proton Synchrotron (SPS). This was initially hampered by vacuum issues in several critical components, such as RF cavities and kicker magnets, requiring extensive scrubbing campaigns to condition them. This paper reviews the current status of the high brightness LHC beams in the SPS, including commissioning evolution, aspects related to beam stability and beam optimization and the current brightness reach. An assessment of the operational readiness of these beams for the High Luminosity LHC era is also given.

INTRODUCTION

The LHC Injectors Upgrade (LIU) Project [1] has been put in place to prepare the CERN injectors complex for the delivery of high brightness beams to the LHC during the High Luminosity LHC (HL-LHC) era [2]. With the end of the second LHC Long Shutdown (LS2), the implementation of all the hardware upgrades in the scope of the project was completed. Since 2021, final commissioning of the LIU beams has been taking place throughout the complex in parallel to physics delivery.

The Super Proton Synchrotron (SPS) is the final accelerator in the CERN LHC injector chain [3], and was the last machine to complete commissioning of LIU beams – following the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS). The SPS accelerates protons to 450 GeV/c before it injects the beams into the LHC. This paper will outline the path towards achieving the parameters of the LIU beams with its challenges and milestones for the SPS from the post-LS2 recommissioning in the beginning of 2021, until these parameters were reached at the beginning of 2025.

KEY SPS UPGRADES FOR LIU BEAMS

The LIU beam parameters are extensively summarized in [1]. For this paper, it is sufficient to recall that for the SPS the aim was to achieve a bunch intensity of 2.3e11 ppb at transverse emittances of 2.1 um and a bunch length of 1.65 ns±10% at 450 GeV/c in 4 batches of 72 bunches with a bunch spacing of 25 ns.

To be able to provide LIU beams, one of the key upgrades in the SPS was the reconfiguration and renovation of its Radio Frequency (RF) system. This involved a major RF power upgrade as well as a complete redesign of the low-level RF system [4–6]. The SPS beam dump system was also relocated and redesigned to be able to sustain the repeated impact of the high brightness beams [7]. This involved an upgrade of the beam dump block as well as the dump kickers system, which now consists of three horizontal and three vertical deflecting kickers (MKDH and MKDV) to sweep the beam across the face of the dump block.

These upgrades introduced critical components which have been particularly challenging to condition with the high-intensity beams.

YEARLY SCRUBBING RUNS

After each Long Shutdown and each Year-End Technical Stop (YETS), a so-called scrubbing run is conducted in the SPS at the beginning of every operational year. This consists of extended periods with LHC type beams, gradually ramping-up in intensity ramp-up for overall machine conditioning.

Figure 1 shows the intensity evolution during the 2024 scrubbing run. Three different types of cycles were used throughout the scrubbing run. The reasons for this will be highlighted in the next section. The increase of the intensity, especially at the beginning of the run, is clearly visible.

LIU BEAM PARAMETER ACHIEVEMENT

The effectiveness of scrubbing relies on the ability to operate the machine under conditions with considerable outgassing. The machine has to be operated close to the vacuum interlock level, while avoiding sudden pressure spikes, sparking and e-cloud induced instabilities. The art of scrubbing is to master this balance between pushing gently but steadily towards increasing intensity and energy, while running stably close to the vacuum threshold limits of the critical components throughout this process. Several procedures and techniques have been invented and deployed over the past few years to achieve this.

As an example, for the injection kickers (MKP) as well as the MKDH, critical outgassing would only occur with short bunch lengths, i.e. at the highest energy of 450 GeV/c (referred to as “flat top”). Since the standard scrubbing cycle only featured a rather short flat top, a special scrubbing cycle was designed with an extended flat top to effectively increase the scrubbing duty cycle for these components. Longitudinal blow-up was used to tailor the bunch length throughout this process to maximize outgassing while remaining in a stable situation.

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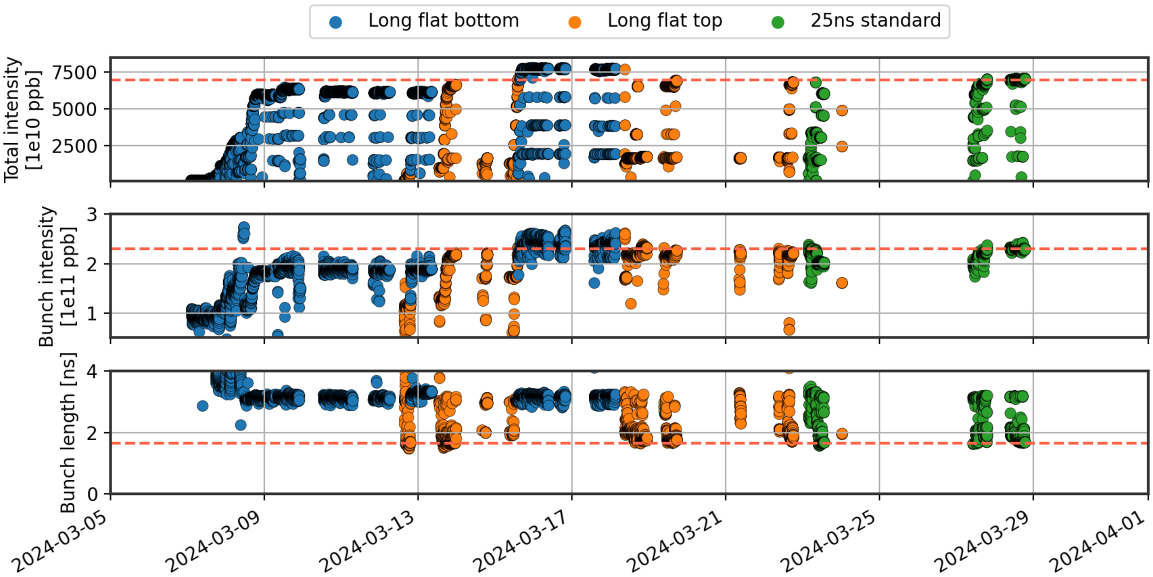

Figure 1: Evolution of beam parameters during the 2024 scrubbing run. The different colors correspond to the different scrubbing cycles used in the SPS.

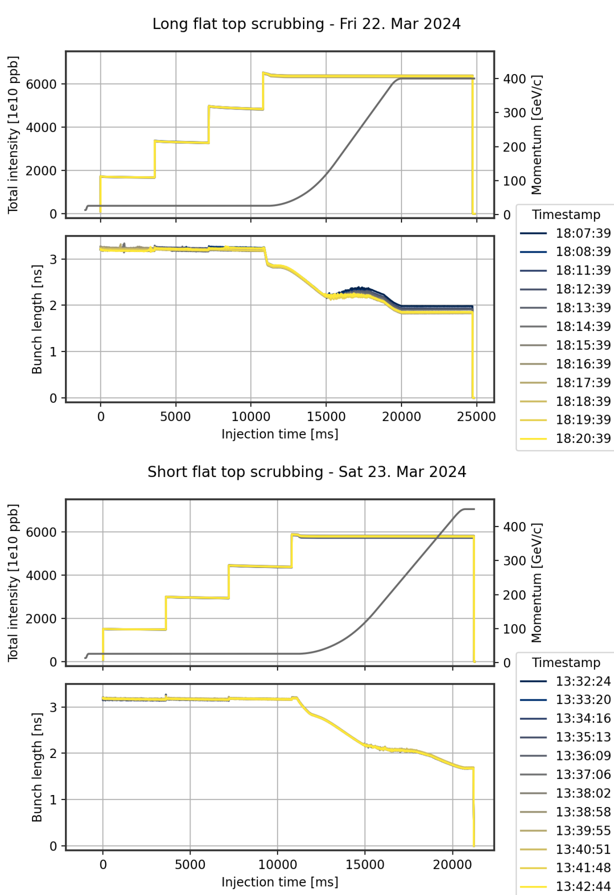

Figure 2: Scrubbing run in 2024. The plots show the intensity, energy, and bunch length evolution during a scrubbing cycle played in the SPS; the top plot shows the long flat top scrubbing cycle, and the bottom plot shows the nominal scrubbing cycle.

Excessive beam-induced kicker heating also limited scrubbing by imposing long idle times to allow for kicker cooling. This was mitigated in 2023 by replacing the kicker exhibiting the highest heating rate with a new, impedance-optimized version. This led to a considerable increase of the scrubbing duty cycle [8].

Figure 2 shows the beam intensity and beam energy along the scrubbing cycles with the long and nominal flat top, respectively. These were cycles played during the scrubbing run in 2024, using 4 injections of 72 bunches at around 2.1e11 ppb for a total beam intensity of more than 6000e10 protons. It is clearly visible how the longitudinal blow-up is used to maintain the bunch length at the optimal level for scrubbing.

The full set of LIU beam parameters, including the per-bunch intensity, transverse emittances and bunch length at flat top, was finally achieved during the 2025 scrubbing run. The scrubbing process is shown in Fig. 3 where the scrubbing cycle with nominal flat top was used, the same cycle that is foreseen to be the production cycle for filling in the HL-LHC era. The gradual intensity ramp-up is clearly visible in the time evolution of the intensity, with the gradual increase in the energy that can be stably reached reflected in the color code of the scatter plot. The achievable energy is governed by the vacuum activity of critical components. Upon elevated activity, the time (and hence energy) at which beam is dumped in the energy ramp is maintained until the activity has calmed down; only then is it pushed further towards the end of the acceleration cycle.

Figure 4 shows how the total beam intensity and bunch length change along the acceleration cycle when the LIU parameters are finally reached. Figure 5 shows the corresponding transverse emittance measurements at the end of

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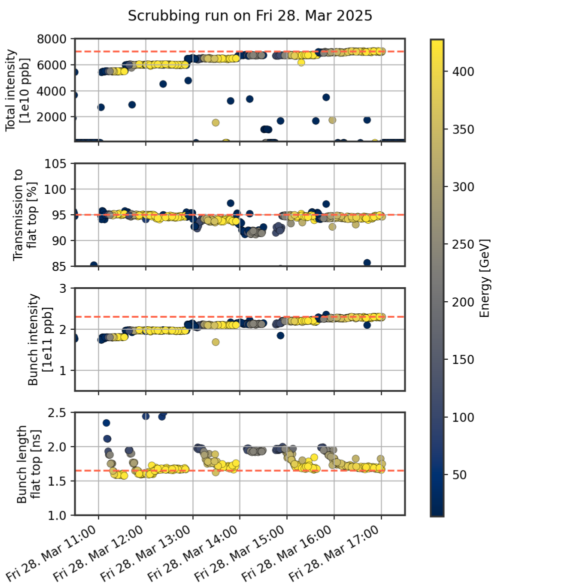

Figure 3: Evolution of beam parameters towards achieving LIU specifications during the 2025 scrubbing run. The gradual progression in total beam intensity, along with the slow increase in the achievable energy, is depicted.

the injection process (no significant emittance increase is observed once moving into the acceleration ramp). More details on the longitudinal parameters are detailed elsewhere in these proceedings [6].

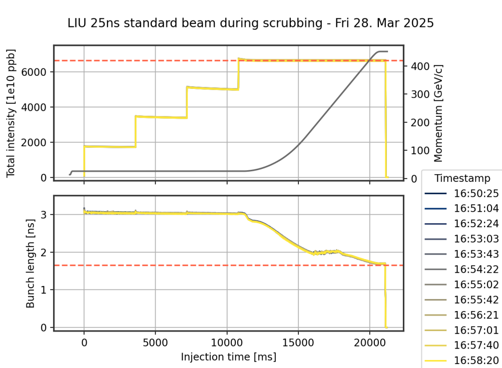

Figure 4: Final period of total intensity, beam energy, and bunch length evolution along the cycle upon achievement of LIU parameters.

To achieve the LIU emittances, the transverse tunes were optimized on the injection flat bottom. With nominal tunes of $Q_x/Q_y = 20.13/20.18$, emittance growth was observed along the flat bottom due to space charge effects, which induce tune spreads of $\delta Q_y^{\mathrm{SC}} \approx 0.2$ and push particles near the integer resonance. To counteract this, tunes were increased for the first injection to $Q_x/Q_y = 20.16/20.22$ and then decreased stepwise at each subsequent injection to preserve beam transmission. This strategy effectively reduced emittance growth and enabled reaching the LIU targets at flat top.

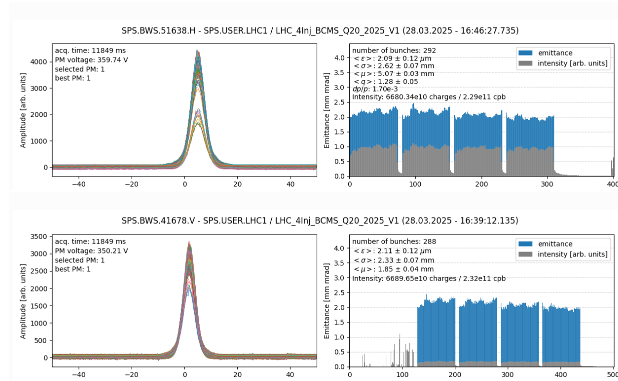

Figure 5: Image of the wirescanner measurements in the horizontal and vertical planes; the emittance is shown for 4 x 72 bunches at the end of flat bottom.

Figure 6 shows the parameters achieved on the limitation diagram for both the standard 25 ns (left) as well as the special higher-brightness BCMS (batch-compression, merging and splitting) (right) beams.

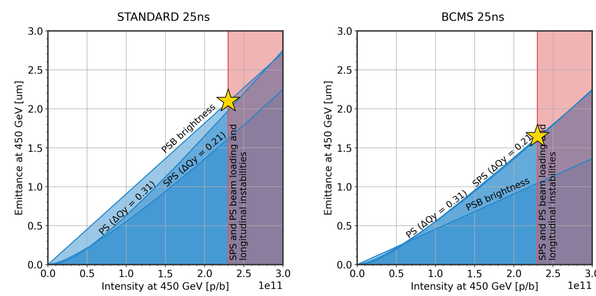

Figure 6: The transverse beam parameters achieved for both the standard 25 ns beam (4 x 72 bunches) as well as the BCMS beam (5 x 48 bunches); it is important to note that the nominal bunch length of 1.65 ns at flat top was consistently achieved for both beams as well.

CONCLUSION & OUTLOOK

A lot of progress has been made since the LIU beam commissioning started in the SPS after the full deployment of all LIU upgraded hardware during LS2. Several machine and beam dynamics limitations have been overcome, with the official SPS LIU beam parameters successfully attained after the 2025 scrubbing run.

Currently, the intensity ramp-up is still an expert-driven process and is time-intensive and tedious. It will now be important to establish and demonstrate the reproducibility and operational reliability during an LIU reliability run, currently planned for 2026, before the start of the next Long Shutdown.

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