INTENSITY REACH IN THE CERN PSB WITH THE HIGH-CURRENT LINAC4 SOURCE

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Abstract

The CERN Proton Synchrotron Booster (PSB) was upgraded within the LHC Injectors Upgrade (LIU) project. The PSB delivers high-brightness beams for collisions at the LHC as well as a large variety of high-intensity beams for fixed target experiments. In the context of the Physics Beyond Colliders (PBC) study and in view of a possible upgrade of the ISOLDE experimental area, an increase of the beam intensity from the present 0.8×10^{13} to up to 1.6×10^{13} particles per ring are considered. High-intensity tests have thus been performed during machine development studies in 2023 injecting the nominal or higher beam current from Linac4. In this contribution, the intensity reach and the main performance limitations for the production of high-intensity beams in the PSB are presented. The results are compared to numerical simulations.

INTRODUCTION

The Proton Synchrotron Booster (PSB) provides beams to the LHC and to various fixed target experiments with intensities ranging from a few 10^{10} up to 10^{13} protons per ring. In the framework of the LHC Injectors Upgrade (LIU) project [1], the PSB received major upgrades during the Long Shutdown 2 (LS2) and subsequently successfully delivered high-brightness beams within the LIU project target parameters [2]. The potential of the upgraded injectors and the possible benefits to the high-intensity beams of the fixed target experiments are being investigated within the Physics Beyond Colliders (PBC) [3] study.

For over 30 years the PSB has been directly delivering beams to ISOLDE [4], a radioactive isotope facility at CERN. To satisfy the demands of ISOLDE for high-intensity beams, the PSB operated before LS2 in the space charge dominated regime with considerable beam losses at injection, also caused by the multi-turn injection scheme. One of the most important upgrades within LIU was the replacement of Linac2, which delivered protons at a kinetic energy of 50 MeV, by Linac4 (L4) that delivers H^- ions at an increased kinetic energy of 160 MeV. The increase of the injection energy in the PSB allows doubling the beam intensity while maintaining similar space charge detuning and transverse emittances.

To convert the H^- ions of L4 to protons, the conventional proton multi-turn injection was replaced by a new charge exchange injection system. In this system, the incoming H^- pass through a thin foil which strips their electrons. The remaining protons are put into orbit around the PSB while the partially or unstripped particles end up in the H^0/H^- dump. The installation of a charge exchange system allows the production of high intensity and high brightness beams with an almost loss-free injection. Furthermore, adjusting closed orbit bumps in the horizontal plane allows the tailoring of the beam emittances in terms of phase space painting, which helps reducing the phase space density and thus space charge forces at high intensities [5].

Figure 1 highlights the importance of the upgrade of the PSB injection region. The two curves show the beam intensity of a typical operational cycle to ISOLDE in 2018 before the upgrade (in red) and in 2023 after the upgrade (in green). It is evident that in order to have approximately 0.8×10^{13} protons per ring at extraction, more than 1.1×10^{13} protons had to be injected in 2018, as 25% of the beam would be lost within the first 100 milliseconds. In 2023, after the LIU upgrades and the optimization of the injection, as well as transverse and longitudinal beam characteristics, the 0.8×10^{13} protons per ring at extraction are achieved with a transmission of more than 99%.

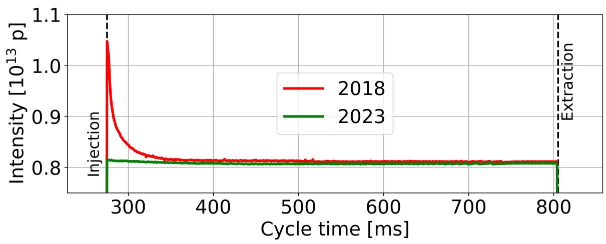

Figure 1: Operational beam intensity for PSB ring 4 for an ISOLDE beam in 2018 (red) and 2023 (green).

HIGH INTENSITY STUDIES

With the LIU upgrades and the L4 capabilities, both the available beam current at injection and the injection efficiency in the PSB have been improved. Consequently, a series of studies were performed in 2023 to explore a new regime for the high intensity operations. These studies also serve as a basis for the future PSB operations to clarify and facilitate the need of future upgrades and consolidation of the ISOLDE facility.

The nominal operation of L4 is based on a current of 35 mA generated from the source, translating to 25 mA before chopping at PSB injection ("nominal L4 current configuration") when considering the transmission through the RFQ. In 2023, a new H^- source was put in operation for the

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L4 [6], which allows for even higher beam current to the PSB. In particular, the new IS04 source allows generating 50 mA, which translates to 35 mA before chopping at PSB injection ("high L4 current configuration"). Studies injecting high intensity in the PSB were performed in 2023 with both the nominal and the high L4 current configurations. It should be noted that the total injected intensity in the PSB does not change with the two different configurations as the number of injected turns needs to be adjusted to remain within the present hardware limitations of the H^0/H^- dump.

The top graph of Fig. 2 shows the beam intensity at injection and extraction for the PSB ring 4 during the high intensity measurements in October 2023 with the high L4 current. Although the maximum number of turns that can be injected by L4 to each ring of the PSB is 148, corresponding to a 600μs pulse length, this number was limited to 100 to protect the H^0/H^- dump. This corresponds to $1.60 - 1.65 \times 10^{13}$ protons at injection for a 740 ns pulse length per turn. The maximum intensity that was extracted exceeded 1.6×10^{13} protons per ring, which is twice the intensity presently requested by the ISOLDE facility and higher than the 1.5×10^{13} assumed for a potential upgrade. The step-like variations of the injected beam intensity in Fig. 2 can be attributed to L4 parameter manipulations, such as changes of the injected pulse length and number of turns, while manipulations of the PSB parameters, such as transverse tunes, transverse painting and RF voltage programs resulted in variations of the extracted beam intensity.

The bottom graph of Fig. 2 shows the beam transmission from PSB injection to PSB extraction for the same time period. In the initial configuration, at which only the number of turns was adapted, the transmission was of the order of 95%. A beam capture with a triple harmonic RF bucket was used because of two major advantages: it reduces the longitudinal peak line density and subsequently the maximum space charge tune spread, and also allows longer bunches to be injected from Linac4 with reduced mismatch [7]. The reduction of the particle density is achieved also in the horizontal beam profile by means of transverse painting [8], which was empirically adjusted. The working point was also modified with respect to the initial configuration, $(Q_x^{\text{init}}, Q_y^{\text{init}}) = (4.22, 4.36)$, and was set to $(Q_x, Q_y) = (4.235, 4.4)$ at injection to accommodate a larger space charge tune spread. The optimal configuration for the working point evolution along the cycle and the painting bump function during the injection process are shown in the top and bottom graphs of Fig. 3 respectively. Compensation of the octupole resonances was applied along the cycle, using additional octupoles to redistribute and minimize the current requirements. Furthermore, even though in normal operations no orbit correction is applied, as the RMS orbit is below ≈ 2 mm in both horizontal and vertical planes all along the cycle, correction to the ≤ 1.5 mm level along the cycle in both planes was needed to minimize losses in this configuration. A further increase in transmission was achieved by increasing the maximum total RF voltage to 23 kV, to increase the area of the bucket, and also by applying corrections to the disturbed magnetic field to minimize the excursion in the radial beam position. Finally, the removal of the small mask, an absorber which serves as aperture restriction for localising the losses in the machine, gave an additional margin in the accumulated beam intensity. In the optimal configuration, the 1.6×10^{13} protons per ring were extracted with a transmission of well beyond 97%.

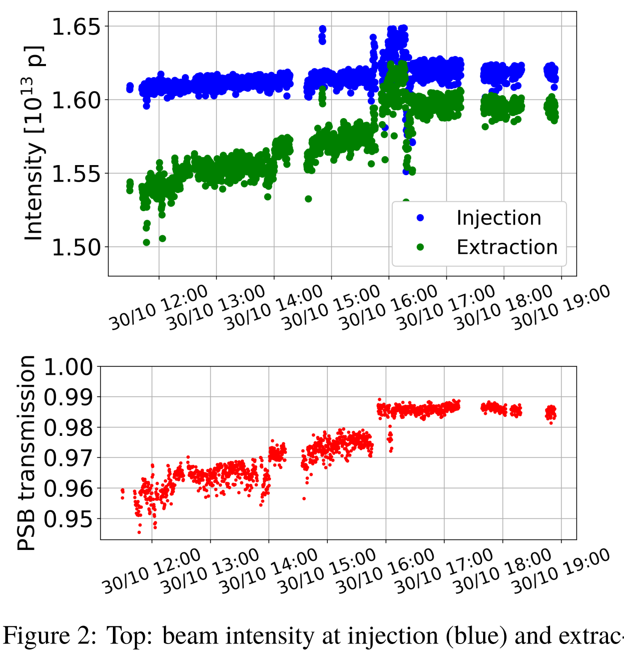

Figure 2: Top: beam intensity at injection (blue) and extraction (green) of the PSB ring 4 during the high intensity tests with the "high L4 current" configuration. Bottom: beam transmission between injection and extraction for the same time period.

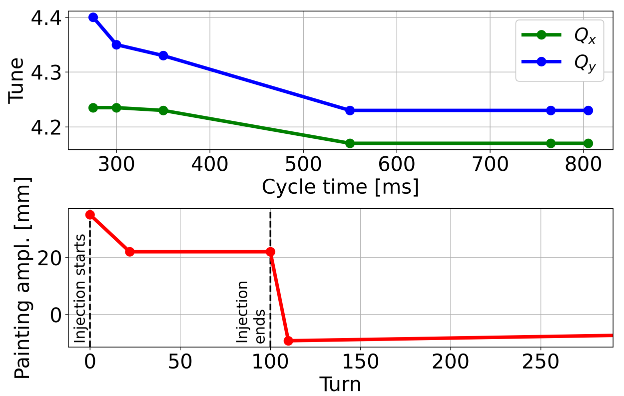

Figure 3: Top: optimal evolution of the horizontal (green) and the vertical (blue) tunes. Bottom: optimal function for the painting bump.

The intensity reach of the PSB rings 2 and 3 was similar to ring 4. No high intensity tests were performed in ring 1 due to different hardware configuration in the RF amplifiers which made it more prone to failure at these intensities. These amplifiers were modified at the end of 2023 [10] and high intensity measurements in R1 are planned for 2024. High intensity measurements were performed throughout 2023 also with the nominal L4 current. The extracted intensity and transmission were similar to the ones of the high L4 current (obviously with higher number of turns injected). No obvious benefits or bottlenecks were identified for the beam production in the PSB when using the high L4 current configuration compared to the nominal L4 current configuration.

Although the PSB is already close to the maximum intensity that can be injected without further upgrades (L4 current limited by klystrons and H^0/H^- dump), work is ongoing to maximise the transmission and the machine reproducibility. For intensities $\leq 1.5 \times 10^{13}$ protons per ring, large shot-to-shot and also day-to-day variations were observed in the transmission. Figure 4 shows the intensity evolution along the cycle, for a high L4 current, at an intensity of 1.6×10^{13} protons per ring and a transmission of more than 97%. The origin of the slow losses occurring in the first 100 ms has not been fully characterized. High intensity studies will continue in 2024 to understand both the transmission fluctuations and the loss evolution along the cycle.

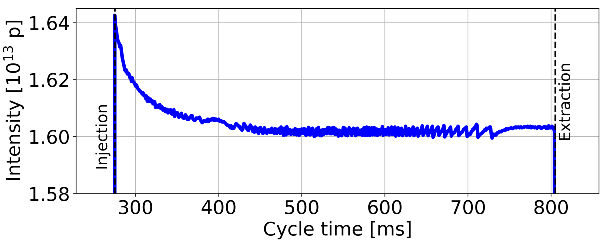

Figure 4: Measured beam intensity evolution during the PSB cycle with the high L4 current, of ring 4. The slow losses at the beginning of the cycle result to a transmission of approximately 98% (0.04×10^{13} particles lost).

TRACKING SIMULATIONS

Work is also ongoing to improve the understanding of the loss mechanisms at high intensities using simulations with Xsuite [9]. Xsuite is a tracking simulation framework developed at CERN, which combines the capabilities of various existing and well-established CERN simulation tools. Many beam dynamics effects have already been incorporated into Xsuite for the purposes of the PSB simulations. The multi-turn charge exchange injection, the dynamic collapse of the injection bump along with the induced fringe fields and eddy currents, the process of transverse painting, the Coulomb scattering during the passages of the beam through the stripping foil, as well as the triple harmonic beam capture have all been modelled and included in the code. The space charge forces are modelled with a 2.5D Particle In Cell algorithm using 500k macroparticles.

Figure 5 compares the beam intensity evolution between the tracking simulation and the measurement of Fig. 4. In the simulation, a realistic L4 particle distribution was tracked for 25k turns (corresponding to approximately 25 ms from PSB injection), including all the previously mentioned effects. The high L4 current configuration with 100 turns injection was assumed and also the tune and painting scheme of Fig. 3. A lattice without β-beating or orbit distortions was assumed. In the simulation, the particles are mostly lost in the vertical aperture. The measured loss rate is stronger than the simulated, and thus the difference in the extracted beam intensity is expected to be larger for t = 300ms. To further improve the agreement between measurement and simulation, a realistic model of the field imperfections needs to be taken into account as well as differences in the tune (including the effects coming from impedance at this high intensity to take into account coherent and incoherent tune shifts) and in the RF voltage settings.

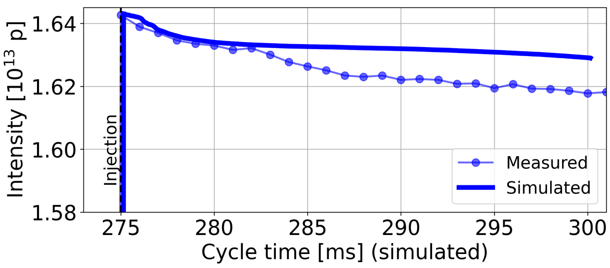

Figure 5: Comparison between the measured (doted line) and simulated (solid line) beam intensity of the high L4 current configuration. The simulation is performed with Xsuite.

SUMMARY

High-intensity tests were performed in 2023 to explore the full potential of the PSB after the LIU upgrades. A beam intensity of more than 1.6×10^{13} protons per ring was extracted for the first time with a transmission of more than 97%. This achievement was made possible thanks to the LIU upgrade with the increased injection energy, the H^- injection system and the L4 capabilities, the transverse painting, the transverse tune control, the resonance compensation, and the triple harmonic capture. The challenges to understand the loss mechanisms and the machine reproducibility, to further improve the beam quality at these parameter regimes, are being addressed both in measurements and simulations.

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