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PERFORMANCE IMPROVEMENT STUDIES OF THE FIXED TARGET BEAMS ALONG THE CERN INJECTOR CHAIN

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Abstract

Within the LHC Injectors Upgrade (LIU) project, LHC injectors received major upgrades that resulted in an unprecedented beam brightness. In the framework of the Physics Beyond Colliders (PBC) study, the full potential of the upgraded injectors is being explored for the improvement of the Fixed Target (FT) beams as well. This contribution details recent studies on beam transmission and beam quality along the injectors of the SPS Fixed Target PROton (SFTPRO) beams for the North Area (NA) experiments. In particular, possibilities of tailoring the transverse emittances out of the PSB and the impact on the beam transmission in the SPS are shown. Furthermore, the impact of the transverse damper excitation on the efficiency of the Multi-Turn-Extraction in the PS are discussed. Finally, the main factors that limit the intensity reach of the injectors are also discussed.

INTRODUCTION

Besides the LHC and its large experiments, CERN hosts a rich program of Fixed Target (FT) experiments throughout its accelerator complex. In the past years, the LHC injectors have provided beams to the FT experiments with a wide range of beam intensities and emittances. The recent upgrades of the injectors within the LHC Injectors Upgrade (LIU) project [1] improved not only the high-brightness beams, aimed for the HL-LHC runs, but also the high-intensity FT beams. The full exploitation of the new capabilities of the upgraded injectors is being addressed within the Physics Beyond Colliders (PBC) study [2].

The Super Proton Synchrotron (SPS) serves a number of FT experiments located in the North Area (NA), which require intense proton and ion beams. Proton beams are usually referred to as the SPS Fixed Targed PROtons (SFTPRO) beams and their production in the injectors is very demanding. In the four rings of the Proton Synchrotron Booster (PSB), the intensity of the SFTPRO beam can reach $\geq 600 \times 10^{10}$ protons per ring. Each PSB ring has a single bunch which is split in two during acceleration to a kinetic energy of 2 GeV. The 8 bunches (2 per ring) are then transferred to the Proton Synchrotron (PS), which accelerates them to a momentum of 14 GeV/c. In the PS, beams undergo transverse and longitudinal manipulations (transition crossing, longitudinal blow-up, bunch splitting, debunching) before being extracted over five turns using the Multi-Turn Extraction (MTE) technique [3]. Finally two injections from the PS are needed for the SPS, that accelerates the beam to 400 GeV. Extraction towards the NA experiments is done using resonant slow extraction [4].

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A new high-intensity Beam Dump Facility (BDF) with the SHiP (Search for Hidden Particles) experiment [5] will be installed in the Experimental Cavern North 3 (ECN3) of the NA between 2026–2030. The SHiP experiment aims at receiving 4×10^{19} protons on target per year from the SPS, which puts strong requirements on the produced beam intensity (SHiP baseline considers 4.2×10^{13} protons per pulse at extraction from the SPS) and the time sharing with the other FT experiments served by the injectors. To match these requirements and improve the beam performance, numerous studies are ongoing to identify and overcome possible limitations in the accelerators. This contribution is focusing on the SFTPRO beams and in particular on their transmission along the injector chain and how this is affected by the beam transverse size and shape.

PROTON SYNCHROTRON BOOSTER

Recent studies have shown that intensities of up to 1600×10^{10} can be achieved in the PSB [6], which is largely sufficient for the SFTPRO beams even for the future requests of SHiP (e.g. 1000×10^{10} protons per PSB ring would result in almost 8×10^{13} protons per pulse in the SPS for an ideal transmission of 100 %). The PSB transmission from injection to extraction is usually close to 99%.

At the injection energy of 160 MeV the maximum space charge detuning can exceed values of $\delta Q^{SC}_{x,y} = -0.5$, and thus particles can interact with the resonances at the integer tunes ($Q_{x,y} = 4.0$). The 4$^{\text{th}}$ order systematic resonances $4Q_x$=16 and $4Q_y$=16 are strongly excited by the space charge potential (due to the lattice periodicity of 16) [7], in combination with all other random field errors, and may result in beam degradation such as transverse emittance growth and beam losses. The beam quality degradation mechanisms have been identified in terms of periodic resonance crossing due to the modulation of the space charge detuning in bunched beams [8]. To minimize the induced emittance blow-up in the PSB, the working point at injection is usually set to relatively high values, i.e. $Q_{x,y} > 4.40$.

A typical working point evolution for the SFTPRO beam is shown in Fig. 1. The top plot shows the horizontal and vertical tune evolution from injection to extraction of the PSB. The bottom plot shows the working point at the cycle times of t=300 ms, t=400 ms and t =670 ms along with the analytically estimated tune spreads from space charge [9]. At injection, in which the space charge tune spread is the largest, a high vertical tune is set to maintain a small vertical emittance, which is desirable for the transmission along the injectors (in particular for the SPS). On the other hand, the horizontal tune is set to Q_x=4.18 at injection to be far from

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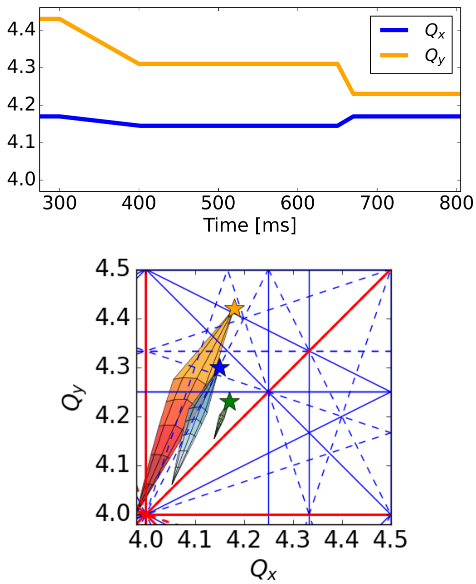

Figure 1: Top: horizontal (blue) and vertical (orange) tune evolution along the PSB cycle. Bottom: working point at t=300 ms (orange), t=400 ms (blue) and t=670 ms (green) in the tune diagram. Up to fourth order resonances are plotted. The shaded areas represent the analytical estimation of the space charge tune spread using PySCRDT [9].

the Montague resonance $2Q_x-2Q_y$ [10] and avoid emittance exchange between the planes leading to an increase of the vertical emittance. Since the horizontal tune is much closer to Q_x=4.0, the horizontal emittance is relatively large, as required for the MTE from the PS to the SPS. The tune spread at PSB extraction is more than 10 times smaller compared to the tune spread at injection because the space charge forces become weaker at higher energies.

By adjusting the working point at injection, horizontal and vertical emittances can be tailored. Figure 2 shows how different vertical tunes near injection lead to different vertical beam profiles and emittances. Here the horizontal tune is kept fixed at Q_x=4.18 as well as the beam intensity to approximately 600×10^{10} protons per ring. For a vertical tune far from the integer resonance, i.e. Q_y=4.43, the vertical emittance is 3.6 µm. As the vertical tune decreases and approaches resonances at the integer tune Q_y=4.0, the vertical emittance grows. At Q_y=4.37 the vertical emittance has increased to 4.2 µm, and at Q_y=4.31 to 5.1 µm.

As can be seen in Fig. 1, the tune spread at injection overlaps with higher order resonances as well. 3rd and 4th-order resonances have been observed to be naturally excited in the PSB [11]. Although they are much weaker than integer-tune resonances, they can still impact beam losses and/or halo formation. Operationally, these resonances are compensated using sextupole and octupole correctors [12], but some residual resonance excitation remains.

At lower beam intensities, the space charge force and hence the induced tune spread is smaller. In this case, the beam is more sensitive to the effects of residual excitation of higher order resonances rather than integer ones. It has been observed that at higher working points, the beam core

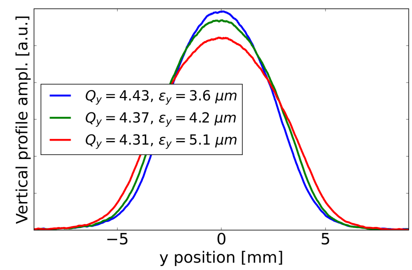

Figure 2: Measured vertical beam profiles for the different working points at injection for a beam intensity of $N_b \approx 600 \times 10^{10}$ protons per ring. The vertical emittance is ϵ_y = 3.6 µm for Q_y = 4.43 (blue), ϵ_y = 4.2 µm for Q_y = 4.37 (green) and ϵ_y = 5.1 µm for Q_y = 4.31 (red).

size decreases but the high-amplitude particle population increases. This effect distorts the transverse beam distribution making it a heavy (overpopulated) tailed Gaussian [13]. The tail seems to contribute in the transmission degradation of the downstream accelerators, as will be discussed in the next paragraphs.

PROTON SYNCHROTRON

8 SFTPRO bunches are injected from the 4 PSB rings into the PS with a transmission above 99%. The beam transmission in the PS ring, i.e. from injection to extraction, is not a concern as it was ≈99% for $\geq 1000 \times 10^{10}$ protons in 2023, compared to ≈98% for $\geq 2100 \times 10^{10}$ protons in 2022.

SFTPRO beams are extracted using the MTE technique, which magnetically splits the beam transversely into five beamlets, i.e.≈4 islands and the core, by crossing a 4th-order resonance in the horizontal plane. The splitting is fine-tuned by adjusting the horizontal tune and using a transverse exciter to control the beam intensity in the beamlets. In particular, the frequency and amplitude of the excitation are adjusted such that the population of each of the 4 islands is equalized to the one of the beam core, usually referred as splitting efficiency η_{MTE} = 0.2. The RF upgrades deployed as part of LIU allowed the generation of a barrier-bucket [14] that reduces the beam losses during the extraction process of the SFTPRO beam by a kicker gap, and was put in operation in 2023. During high-intensity tests, the longitudinal stability of the beam was demonstrated with the barrier-bucket up to 3300×10^{10} protons [15].

SUPER PROTON SYNCHROTRON

Operationally, two PS injections of the SFTPRO beam are made in the SPS. The transmission of the first injection between PS and SPS varies with intensity and ranges between 92% to 97%. The reasons for this loss in transmission have not been yet fully identified. A possible candidate to contribute in this transmission loss is assumed to be the vertical size of the SFTPRO beams due to the more strict aperture restrictions in the vertical plane of the SPS.

To test the impact of the vertical emittance of the PS-to-SPS transmission, an experiment was set up. In this experiment, two beam intensities were used: a relatively

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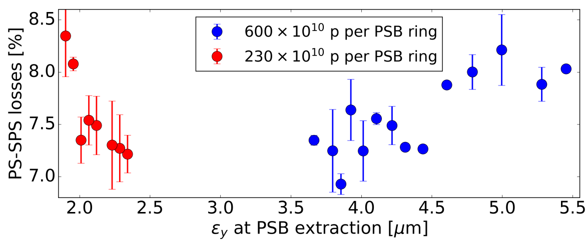

Figure 3: Measured beam losses between PS extraction and SPS flat bottom (5 ms after injection) as a function of the measured vertical emittance ϵ_y at PSB extraction. Blue (red) points correspond to a beam intensity of $\approx 600 \times 10^{10}$ (230×10^{10}) protons per PSB ring.

high-intensity variant, at approximately 600×10^{10} protons per PSB ring ($\approx 2300 \times 10^{10}$ protons at SPS injection), and a low-intensity variant, at approximately 230×10^{10} protons per PSB ring ($\approx 900 \times 10^{10}$ protons at SPS injection). For both beams, the vertical emittance was tailored in the PSB changing the vertical tune at injection, while keeping the horizontal tune constant. At extraction from the PSB, the vertical emittance ranged between 3.5 to 5.5 μm for the high-intensity variant and between 1.8 to 2.4 μm for the low-intensity variant. For all emittances, both beam variants were transferred to the PS. No significant changes in the PS parameters were made for the various scenarios. Nevertheless, small adjustments were required in the transverse damper settings for each value of the vertical emittance in order to get a splitting efficiency close to $\eta_{\mathrm{MTE}} = 0.2$. This is because, although the horizontal tune was kept constant in the PSB, a weak variation of the horizontal emittance with the vertical tune of the order of 0.5 μm for both intensities could not be avoided. Finally, the beam was injected in the SPS (single injection) and was dumped just before acceleration. The beam intensity was monitored throughout all injectors simultaneously. The emittance preservation along the injector chain was relatively good, within $5 - 7\%$.

The results are summarized in Fig. 3, which shows beam losses between PS extraction and 5 ms after SPS injection as a function of the vertical emittance at PSB extraction. The data of the high-intensity variant shows weak PS-SPS losses growth on the vertical emittance. By increasing the vertical emittance by almost 2 μm, transmission degraded by only 1%. On the contrary, red points, which correspond to the low-intensity variant, show the opposite dependence: the transmission degrades for smaller emittances. This behavior ressembles the presence of overpopulated beam tails, since, although the beam core is much smaller (less than 2 μm), high-amplitude particles can still be present and induce observable losses. A comparison of a high intensity vertical beam profile at $\epsilon_y \approx 4.2$ μm and a low intensity vertical profile at $\epsilon_y \approx 2.0$ μm showed that the former followed rather a parabolic-like distribution while the latter, a heavy-tailed Gaussian. The extent of the profile beyond 3σ was similar in both cases. This highlights the importance of the beam distribution shape in addition to its vertical size.

The task of identifying the transmission bottlenecks along an accelerator chain is challenging because of the difficulty to isolate the different beam parameters for one or more accelerators. For example, as discussed before, a coupling between the horizontal and vertical emittance tailoring in the PSB is unavoidable. A decomposition of the PS-to-SPS transmission using the available beam intensity monitors in the transfer line showed that the weak variation of the horizontal emittance with the vertical tune in the PSB is measurable in the transmission between the PS and the TT2 transfer line. The adjustment of the transverse excitation for the variations of the horizontal emittance optimizes the splitting efficiency, but it can also make the size of the beam core larger and increase the beam losses during the extraction. Another example is the small but non-negligible transmission variation from PSB injection to PSB extraction with the vertical tune, which is associated with the crossing of the higher order resonances. A careful cross-accelerator monitoring and coordination of the beam parameters is essential for these studies.

Although for these initial studies the beam was dumped early in the cycle of the SPS, the SPS in-ring transmission between injection and extraction needs to be included in the future analysis. In 2023, this transmission was of the order of 94% for the operational beams, which was overall better than 2022, but also the beam intensity was lower [16]. Additionally, significant work is performed for optimizing the slow extraction towards the NA, which in 2023 reduced the beam losses by 25 % in operation, 50% in MDs [17] while another factor of 2 is being targeted with the new crystal technology, and the spill structure using the empty-bucket channelling [18].

SUMMARY AND OUTLOOK

In this contribution, studies of beam transmission along the accelerator chain were shown for SFTPRO beams. By controlling the PSB working point, the transverse emittances were tailored for beams with two different intensities, which were then transferred to the PS and SPS. Beam intensity measurements along the accelerators showed a weak dependence of the PS-to-SPS transmission with vertical emittance, but they also highlighted the importance of beam tails population in the vertical plane.

Transmission studies of the high intensity SFTPRO beams will be resumed in 2024 to identify present and future limitations of the beam production along the accelerator chain, in particular in view of the upcoming SHiP experiment.

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