CHARACTERIZATION OF TRANSVERSE PROFILES ALONG THE LHC INJECTOR CHAIN AT CERN

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Abstract

Following the successful implementation of the LHC Injectors Upgrade (LIU) project, the CERN injectors were re-commissioned in 2021 and have been delivering beam to the LHC since 2022. The operationally delivered brightness was well within the LHC request for 2022. However, heavy population of non-Gaussian tails of the transverse beam profiles were observed. These tails lead to significant losses at LHC injection and can potentially degrade the luminosity reach of the LHC. This paper follows the studies to characterize the transverse profiles along the accelerator chain: the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). The studies presented are aimed at reducing this tail population, and the methodology to measure the emittance and the tail population will also be discussed.

INTRODUCTION

In the first operational year of the LHC following the implementation of the LIU project [1] during the long shutdown 2, the injectors had to reliably provide high quality beams for the LHC experiments. The beam brightness requested by the LHC for 2022 had already been achieved since 2021 in the respective accelerators of the proton injector chain [2]. However, beam quality issues such as heavily populated transverse tails were not addressed until the beams were operationally used in 2022. In order to reduce losses at the LHC injection to acceptable levels, significant transverse scraping had to be applied in the SPS. In fact, the required scraping had to be done at low energy in the SPS, instead of the usual point close to extraction, to keep the machine activation within limits and avoid saturation of beam loss monitor signals. The transverse tails as well as the losses at LHC injection [3] were studied throughout the year in an effort to understand their origin and reduce them.

TRANSVERSE TAILS ALONG THE CYCLE

In addition to the emittances as evaluated from the standard deviation of a Gaussian fit of the beam profile, the q factor of a q-Gaussian fit was also considered to characterize the transverse tails in the CERN injectors. The fits are evaluated from the average profile of all the bunch-by-bunch measurements of the circulating beam in the PS and SPS, and all four rings of the PSB. The q-Gaussian fit has been used to characterize transverse tails in the past both in the LHC [4] and the PSB [5].

Proton Synchrotron Booster (PSB)

At the CERN PSB the brightness for the LHC beams was higher than the LIU target already during the initial year of commissioning [2,6]. However, heavy tails were observed at the PSB extraction for the operational beam, with a q-factor in the order of 1.4. In this regime of intensities, i.e., up to 180×10^{10} protons per ring, the PSB is not dominated by space charge effects, but more by resonances from nonlinearities [7] and errors coming from the injection system [8]. Hence, the working point could be optimized to minimize interaction with nonlinear resonances without affecting the beam brightness. In this optimized configuration, measurements were taken on all 4 PSB rings along the full cycle. The results are summarized in Fig. 1. The tails do not show any significant variation along the cycle and are kept to a q-factor below 1.2. The tails in ring 4, even though smaller than in the initial configuration, are still higher than the other rings. In ring 3 the tails seem to change along the cycle and are not always reproducible as implied by the relatively large errorbars. The tail population in rings 3 and 4 will be thoroughly studied this year to further improve the shape of the profiles.

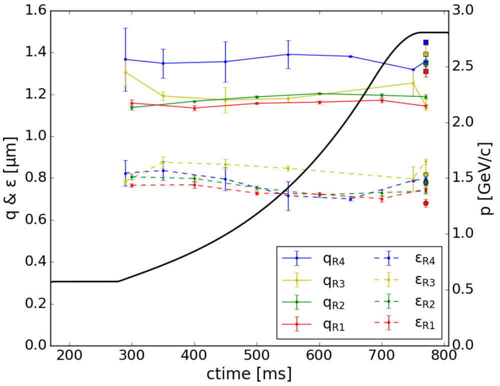

Figure 1: Vertical tails in terms of q-factor (solid lines) and emittances (dashed lines) along the PSB cycle (momentum shown on the right axis) for the optimized beam. The nominal beam parameters, i.e., q-factor and emittance, are measured right before extraction.

Proton Synchrotron (PS)

In the PS, the LHC beam is produced using two injections from the PSB [9]. The transverse profiles are measured after each injection and at the end of the flat top. The results are summarized in Fig. 2 (top). The emittances remain unaffected throughout the cycle while the tails seem to increase from injection to flat top. In order to minimize this

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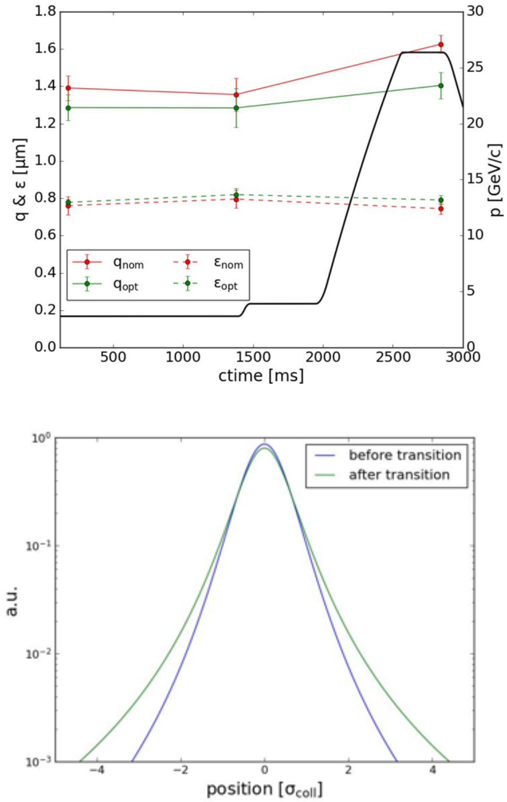

Figure 2: Vertical tails in terms of q-factor (solid lines) and emittances (dashed lines) along the PS cycle (momentum shown on the right axis) for the nominal (red) and optimized (green) beams (top). Vertical profile in logarithmic scale before (blue) and after (green) transition at cycle times 2000 ms and 2030 ms, respectively (bottom).

increase of the tail population, the working point evolution in the PS had to be modified. At low energy, the working point is controlled by the low energy quadrupoles, while at high energy only the Pole Face Windings (PFWs) can be used [10]. In addition, transition crossing occurs at cycle time ≈ 2020 ms [11] and thus the PFWs are used to control the chromaticity and stabilize the beam. In these conditions, the working point at the beginning of acceleration drifts towards high tunes where higher order resonances are dominating the dynamics [12]. The tunes could be slightly decreased while preserving the beam stability. This allowed the tail population increase in the PS to be limited as shown in Fig. 2 (top). The remaining increase of tails along the PS cycle seems to occur directly at transition crossing. This is clearly observed when the profiles measured at cycle time 2000 ms and at 2030 ms are compared in Fig. 2 (bottom). Additional studies will be conducted in 2023 to better characterize the beam during transition crossing in an effort to minimize the transverse tails. Note that horizontal tails cannot be assessed directly in the PSB and the PS due to the large dispersion at the location of the horizontal wire scanners.

Super Proton Synchrotron (SPS)

In the SPS, the profile evolution is characterized using an additional metric, namely the tail extent. The tail extent corresponds to the distance at which the signal of the measured profiles drops below the measurement noise of the baseline. This metric is particularly important in the SPS, as it is the only accelerator in which scraping is applied. In addition, the SPS is the first accelerator of the chain where the measurement of the horizontal tails is possible thanks to the small horizontal dispersion at the wire scanners.

The measurements of the transverse profiles in the SPS are summarized in Fig. 3. In both planes some emittance blow-up is observed during the long flat bottom, as the beam is stored for the accumulation of five injections from the PS. As a result, the tail content seems to reduce due to the modification of the beam profile shape. In addition, slow losses along the flat bottom contribute to the minor reduction of the tail extent. During acceleration the tails are increased both in terms of extent and q-factor. Applying some scraping at the beginning of acceleration in both planes, similar to what is done in routine operation, the tails are reduced, but still re-populate slightly during acceleration. he scraping does not seem to affect the tails at flat top, especially in the

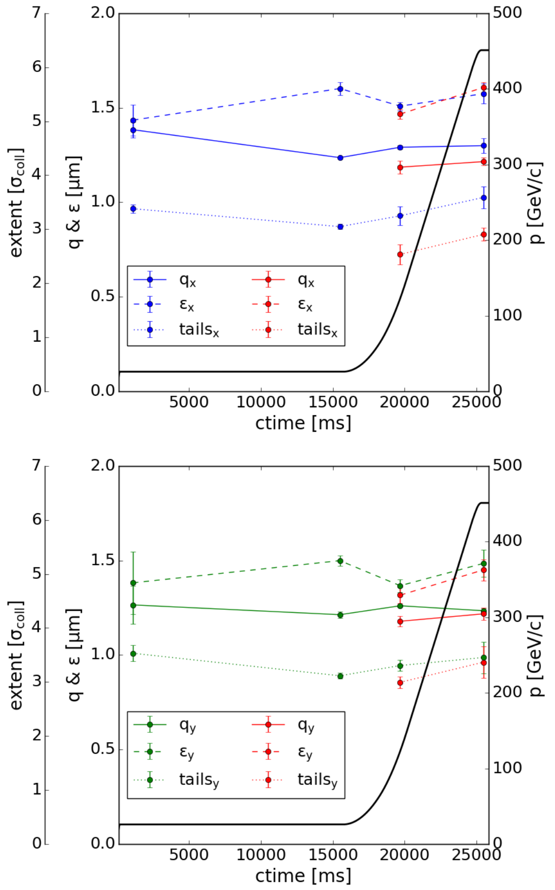

Figure 3: Emittances (dashed) and tail population in terms of q-factor (solid) along the SPS cycle (momentum plotted on the right axis). The tail extent (dotted) is shown on a secondary axis. Horizontal (top) and vertical (bottom) profiles measured with (red) and without scraping (blue and green depending on the transverse plane measured).

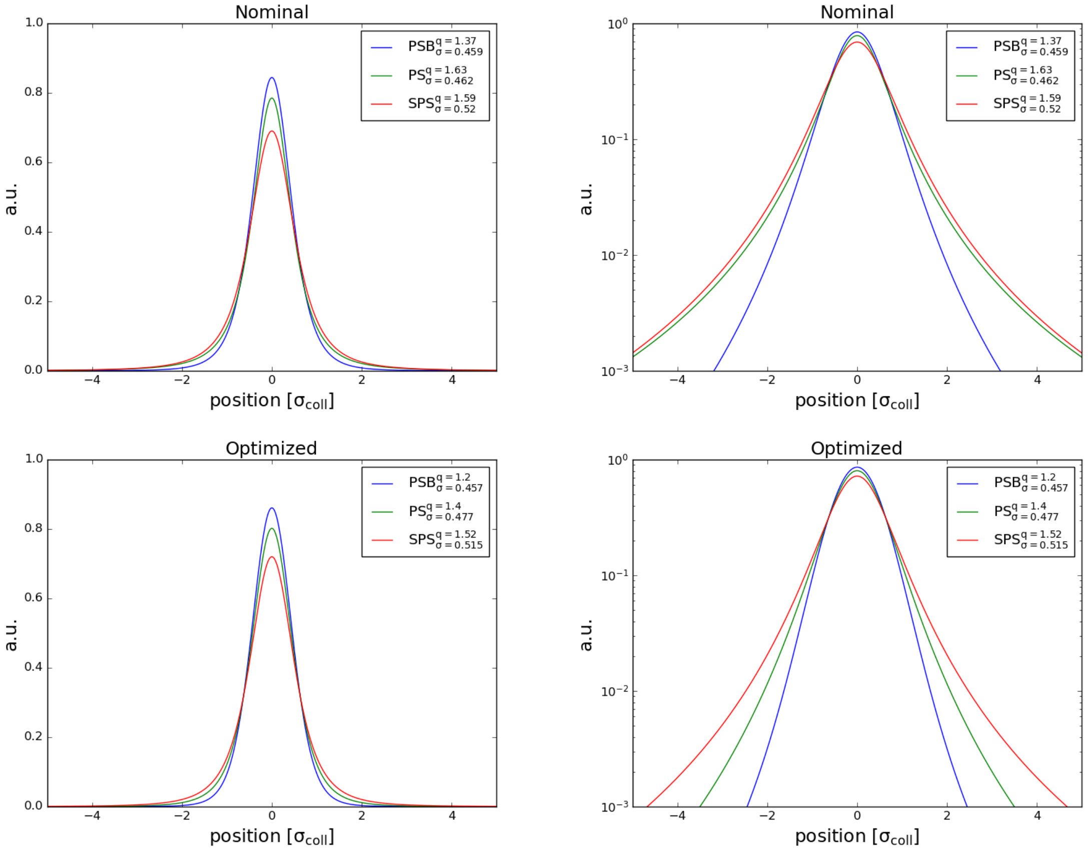

Figure 4: Vertical profiles expressed in units of σ_{coll} (for explanation see text) along the injectors for the nominal (top) and optimized (bottom) variants. Also shown in logarithmic scale to highlight the difference in the tail content (right).

vertical plane. The optimized beam variants from the pre-injectors were tested in the SPS, but reproducibility issues did not allow conclusions to be drawn.

TRANSVERSE TAILS ALONG THE CHAIN

The vertical transverse profiles were measured along the full injector chain in order to follow the tail evolution. The profiles are normalized to collimation sigmas, σ_{coll}, referring to a Gaussian beam distribution with a standard deviation corresponding to an emittance of 3.5 µm. The superposed profiles measured at the PSB and PS extraction and the SPS injection are shown in Fig. 4. In the nominal configuration, heavy tails are observed in the PSB. The tails get further populated in the PS while at SPS injection the measurements are consistent with the results from the PS. In the optimized configurations, the tail content is significantly reduced in both the PSB and the PS as an outcome of the working point optimizations. However, these improvements are not seen at SPS injection, indicating that effects connected to the PS to SPS transfer would also need to be studied to identify potential sources of tail population. Moreover, additional measurements at PS extraction and SPS injection would minimize reproducibility issues leading to a better characterization of the tails. The horizontal profiles would also need to be looked at in both the PSB and PS, since the tails in the SPS are observed in both planes as shown in Fig. 3. In order to avoid the coupling of the longitudinal plane to the horizontal profiles in the PS, the measurements could be taken using a low dispersion optics configuration developed recently [13].

CONCLUSION

The transverse profiles and their evolution along the LHC injector chain were characterized in 2022. The studies were motivated by the significant losses observed at LHC injection, which could only be mitigated with aggressive scraping of the beam in the SPS, mostly in the horizontal plane. Optimizations of the tail content were achieved in the PSB, where the working point evolution along the cycle was adapted to minimize the interaction with resonances, while the beam brightness was maintained. In the PS, the tail content was improved by working point optimizations during acceleration. Additional studies are needed to fully characterize the beam during transition crossing and further improve the distributions. The studies in the SPS showed only minor tail increase during acceleration in both planes. The impact of the different pre-injector variants was not visible at SPS injection, and the reason for that will be studied in 2023.

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