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PUSHING HIGH INTENSITY AND HIGH BRIGHTNESS LIMITS IN THE CERN PSB AFTER THE LIU UPGRADES

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Abstract

After the successful completion of the LHC Injectors Upgrade (LIU) project, the CERN Proton Synchrotron Booster (PSB) has produced beams with up to two times higher brightness. However, the efforts to continuously improve the beam quality for the CERN physics experiments are ongoing. In particular, the high brightness LHC beams show non-Gaussian tails in the transverse profiles that can cause losses in the downstream machines, and even at LHC injection. As a result, alternative production schemes based on triple harmonic capture are being investigated in order to preserve brightness and reduce transverse tails at the same time. In addition, in view of a possible upgrade to the ISOLDE facility that would require approximately twice the number of protons per ring, the ultimate intensity reach of the PSB is explored. In this context, injection schemes using painting both transversely and longitudinally in order to mitigate the strong space charge effects are developed.

INTRODUCTION

The PSB is the first synchrotron of the proton injectors chain at CERN. The most challenging beams in terms of brightness are the ones for LHC and its upgrade, the High-Luminosity LHC [1]. After the successful implementation of the LIU project [2], the PSB has managed to reach the brightness target [3], while issues of beam quality, in particular non-Gaussian tails in the transverse distributions, have been identified [4]. However, the LHC beams are not the most demanding in terms of intensity, as the ISOLDE facility [5] requires almost a factor 3 higher intensity for day to day operations, reaching >800 × 10^{10} Protons Per Ring (ppr). In addition, in the context of the Physics Beyond Colliders (PBC) study [6] and a possible upgrade of the ISOLDE experimental area, intensities up to >1500 × 10^{10} ppr need to be investigated. On the other hand, the beams for the ISOLDE facility are not very demanding in terms of brightness, as the transverse beam size does not pose limitations for the experiments.

The main performance limitations at the PSB for the production of high brightness and high intensity beams are discussed in the following sections. Also alternative operational scenarios to overcome these challenges are proposed.

SPACE CHARGE MITIGATION TECHNIQUES

The main performance limitation for the challenging high brightness and high intensity beams is due to space charge, especially at the injection energy of 160 MeV. In particular, space charge introduces an incoherent tune shift that depends on both transverse and longitudinal beam characteristics. For Gaussian beam distributions the maximum tune shift, corresponding to particles at the center of the beam, is obtained as [7]:

$$\Delta Q_{x,y} = -\frac{r_0 \lambda}{2\pi e \beta^2 \gamma^3} \oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)(\sigma_x(s)+\sigma_y(s))} ds\,, \quad (1)$$

where r_0 is the classical particle radius, λ the longitudinal line density, e the particle charge, $\beta\gamma$ the relativistic factors,

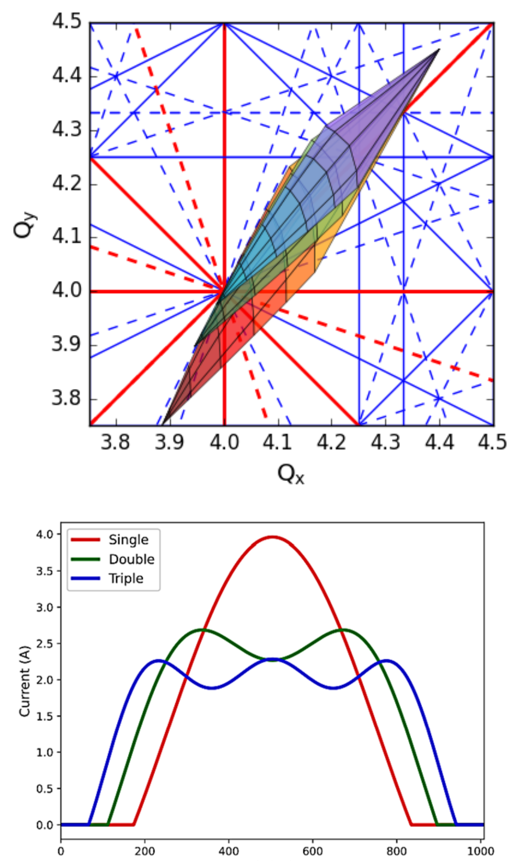

Figure 1: Analytically estimated space charge tune spread [8] at PSB injection for the operational high brightness beams for the single (red), double (green) and triple (blue) cases (bottom). Resonance lines up to 4th order plotted, normal in solid and skew in dashed, systematic in red and non-systematic in blue. Longitudinal line density for the cases of single, double and triple harmonic system (top).

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$\beta_{x,y}$ the transverse β-functions and $\sigma_{x,y}$ the transverse beam sizes.

The space charge induced tune spread at PSB injection can reach values exceeding $\Delta Q_{x,y} \leq -0.5$ as shown in Fig. 1 (top). In order to avoid emittance blow-up and loss of brightness due to interaction with the resonances around the integer tunes, high working points at injection are chosen, i.e. $Q_{x,y} \geq 4.4$. To operate in this regime, resonance compensation schemes have been developed [9] and are updated every year. Furthermore, even higher tunes above the half integer resonance are being investigated [10].

In addition to the exploration of higher tunes to avoid blow-up, one can try to mitigate the space charge tune spread by manipulating the beam characteristics at injection. As from Eq. (1), the available parameters for optimization can be the beam energy, the beam optics and the transverse and longitudinal beam characteristics. The energy change as a means to minimize space charge was one of the main components of the LIU project, during which the PSB injection energy was raised from 50 MeV to 160 MeV. The PSB optics are very regular and thus allow no leverage on the tune spread. Hence, the transverse and longitudinal characteristics, such as the emittances and the line density are the only remaining knobs to manipulate the space charge induced tune spread.

For the high intensity users, where the transverse emittances can be large, the transverse painting [11] can efficiently mitigate space charge for intensities up to $\approx 1000 \times 10^{10}$ ppr. This technique takes advantage of the new H^- charge-exchange injection system [12] to intentionally inject larger emittances and thus reduce the space charge tune spread. However, this manipulation is not efficient enough for the high brightness users for which the transverse emittances need to be as small as possible.

Thus, the only option for further reducing the space charge force is the manipulation of the longitudinal parameters, and in particular the line density at injection. Figure 1 (bottom) shows different line densities that can be achieved using additional RF systems at higher harmonics (always a multiple of the main RF system harmonic number), such as a double and a triple harmonic RF. The impact of these manipulations is affecting the space charge tune spread as shown in Fig. 1 (top). The double harmonic capture is the nominal operational setting for the high brightness and high intensity users in the PSB [13]. However, the triple harmonic capture would give an even larger margin to further boost brightness and in combination with transverse painting allow for even higher intensities. Longitudinal painting can also be applied to better match the injected beam to the PSB RF bucket and get an even better transmission [14].

HIGH BRIGHTNESS BEAMS

The LIU target for brightness in the PSB has been achieved and even exceeded during the first years of operation [3]. However, large non-Gaussian tails have been observed all along the CERN injector chain, while alternative operational scenarios have been deployed to optimize the non space charge dominated regime of operation (i.e. the low intensity regime) for the LHC beams [4, 9]. Currently, the optimization efforts are focusing on the space charge dominated regime. In this respect, the triple harmonic capture minimizing the space charge force at injection has been implemented in the PSB for the LHC beams.

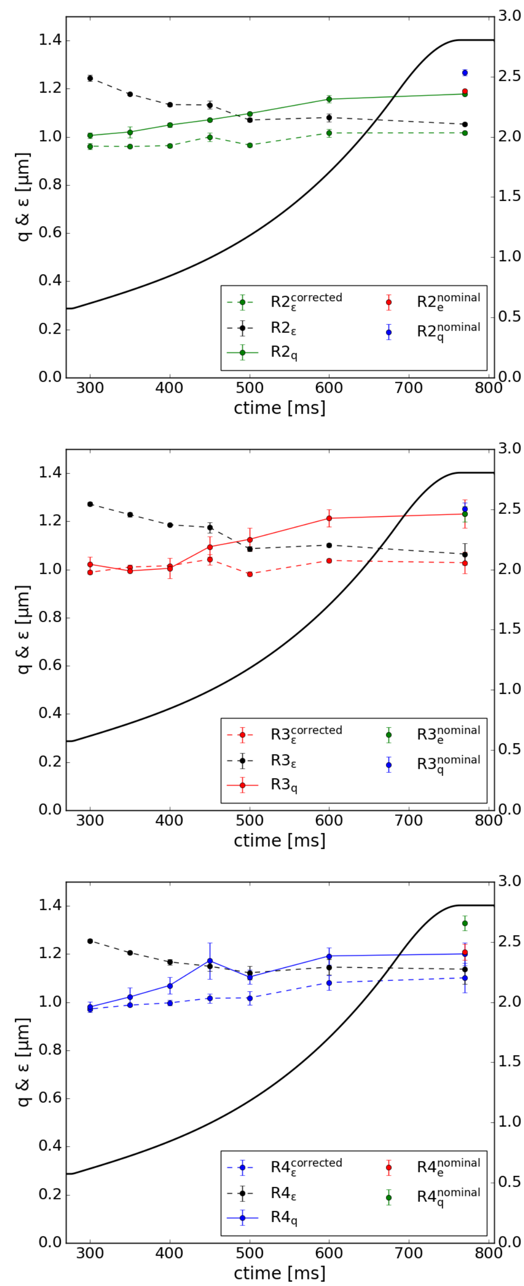

Figure 2: Vertical tails in terms of q-factor (solid lines) and emittances (dashed lines) (as acquired from the WS and correcting for the instrument) along the PSB cycle (momentum shown on the right axis) for the optimized beam with triple harmonic capture. The nominal beam parameters, i.e. q-factor and emittance, are measured right before extraction. Measurements conducted in PSB ring 2 (R2) (top), ring 3 (R3) (middle) and ring 4 (R4) (bottom).

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The lower space charge tune spread at injection allows for modifications of the working point evolution along the cycle. The injection tunes for normal operations are at the $Q_x = 4.4$ / $Q_y = 4.45$ working point as shown in Fig. 1, to avoid emittance blow-up due to resonances around the integer tunes, and they are ramped to a resonance free zone $Q_x = 4.17$ / $Q_y = 4.23$ at higher energy when the tune spread is sufficiently small. However, this implies that the beam interacts with multiple resonances excited by residual magnet errors [15]. Taking advantage of the space charge reduction through the triple harmonic capture, the injection tunes are lowered to $Q_x = 4.31$ / $Q_y = 4.43$ without a loss of brightness. This choice provides a larger distance from the vertical half integer resonance at $Q_y = 4.5$, minimizing the β-beating at injection [16] and avoids interaction with the 3rd order normal resonance at $Q_x = 4.33$. This in turn also allows for better compensation of the 3rd order normal coupling resonance, $Q_x + 2Q_y = 13$, as the simultaneous compensation of two resonance can be avoided. When correcting a single resonance of a given type, such as the 3rd order normal resonance, a smaller number of correctors are needed. In addition, it has been shown that higher magnet strengths than presently available in the PSB would be required to compensate all 3rd order normal resonances globally [9].

The new LHC beam (the beam was produced from three rings in 2023) with the triple harmonic capture performs better than the nominal one both in terms of brightness and tails, as shown in Fig. 2. The higher brightness can be seen from the emittance reduction at extraction with respect to the operational user, observed in all rings. Note that the emittance reduction along the cycle can be attributed to the blow-up induced by the wire scanner (WS) measurement. By correcting the instrumental effects [17–19], the emittance is well preserved along the cycle. In order to characterize the transverse tails, the measured profiles are fitted with a q-Gaussian function [20], for which the factor q varies from $q < 1$ for less than Gaussian tails to $q > 1$ for heavier tails. The resulting q-factors, showcasing the heavy tails are presented in Fig. 2. The tails are minimized for the optimized version as a reduction from $q = 1.3$ to $q = 1.2$ is observed in all rings. Some tail population along the cycle is still observed, however, the effect of the WS would need to be accounted for, as in past measurements it was demonstrated that the tails might appear smaller at the injection energy [19].

HIGH INTENSITY BEAMS

The margin provided by the triple harmonic can be exploited for pushing the intensity reach of the PSB. In addition to the minimization of space charge, the longer bucket allows injecting larger pulses from Linac4 and hence accumulation of even higher intensities per turn. However, once the intensity of $\approx 1000 \times 10^{10}$ ppr is reached, losses, larger than in the operational regime of $\approx 800 \times 10^{10}$ ppr, are observed at low energy. Operating in this region of the tune diagram

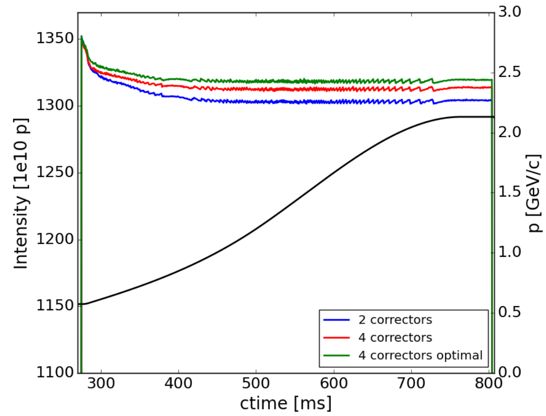

Figure 3: Intensity evolution along the PSB cycle (momentum shown on the right axis) for the high intensity users with a triple harmonic capture. The different intensity curves correspond to different octupole configurations for the compensation of the 4th order normal resonances.

with $Q_x = 4.235$ / $Q_y = 4.38$, the main resonances that cause losses are the 4th order: $4Q_x = 17$, $4Q_y = 17$ and $2Q_x + 2Q_y = 17$. These resonances can be corrected using dedicated octupoles, however, the power supplies are not strong enough to achieve a perfect compensation [15]. The latest resonance compensation studies in the PSB have demonstrated that by combining 4 octupole correctors, the strength of the magnets is effectively doubled and a full compensation can be achieved [21]. Finally, using the latest settings and optimizing the distribution of the required strength among all the available octupoles, the currents in the correctors are minimized and the correction can follow the increase of the magnetic field during acceleration. The impact of these different configurations on the beam intensity is seen in Fig. 3. Overall, the compensation of the 4th order resonances can reduce the losses from 3.6%, with partial compensation, to 2.7% with full compensation and even below 2.4% with the optimization of the current shared between the correctors.

CONCLUSION

The PSB has managed to push the limits for both high intensity and high brightness beams at CERN. In particular, the target for the brightness has been exceeded using a triple harmonic capture to minimize space charge at injection. In addition, the margin provided by this longitudinal manipulation has been used to optimize beam quality and keep the beam profiles closer to the Gaussian distribution. Furthermore, high intensities have been achieved combining transverse painting, careful resonance compensation and the triple harmonic capture. The losses can be kept below the 3% level due to new resonance compensation schemes that optimize not only the resonances crossed and the number of correctors used but also the sharing of the current among the various magnets.

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