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INJECTION CHICANE BETA-BEATING CORRECTION FOR ENHANCING THE BRIGHTNESS OF THE CERN PSB BEAMS

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Abstract

In the context of the LHC Injectors Upgrade Project (LIU), the Proton Synchrotron Booster (PSB) developed an H- charge exchange injection system. The four short rectangular dipoles of the injection chicane induce focusing errors through edge focusing and eddy currents. These errors excite the half-integer resonance $2Q_y = 9$ and cause a dynamically changing beta-beating in the first milliseconds after injection. Using the beta-beating at the positions of two individually powered quadrupoles, measured with k-modulation, correction functions based on a model response matrix have been calculated and applied. Minimizing the beta-beating at injection allows the machine to be operated with betatron tunes closer to the half-integer resonance and therefore with larger space charge tune spreads. In this contribution the results of the beta-beating compensation studies and the impact on the achievable beam brightness limit of the machine are presented.

INTRODUCTION

The LHC Injectors recently underwent major upgrades, as part of the LHC Injectors Upgrade (LIU) project [1], with the aim of achieving the high-intensity and high-brightness beams required by the High Luminosity LHC [2]. As part of these upgrades, the PS Booster (PSB) received a new charge exchange injection region, for converting the negative hydrogen ions (H^-) from Linac4 [3] to protons, at injection.

The main limitation for the beam brightness achievable at the PSB are space charge effects at injection [4]. The Linac4 delivers H^- at an increased energy of 160 MeV, compared to its predecessor, Linac2, which delivered protons at an energy of 50 MeV. The increase of the PSB injection energy mitigates the space charge effects and allows the beam intensity to be doubled while having similar space charge detuning for the same transverse emittances.

The new PSB charge-exchange injection system [5] consists of a horizontal chicane and a thin carbon stripping foil. A set of four, short, pulsed, dipole chicane magnets (BSWs), creating a maximum horizontal bump of 46 mm, have been installed in a short 2.6 m straight section, located at the first sector of the machine, for each of the four PSB rings (16 independently powered magnets in total). The edge focusing of the rectangular BSWs causes quadrupolar field perturbations in the vertical plane. Furthermore, during the ramp-down of the injection chicane, eddy currents are generated in the metallic vacuum chamber, which distort the magnetic field seen by the beam. The eddy currents induce a sextupolar field, proportional to the ramp rate of the BSWs [6]. Since the beam enters the magnets with an offset with respect to the center of the BSWs, the sextupolar component leads to feed-down quadrupolar field perturbations. All these focusing errors cause distortion of the vertical β function around the machine.

At injection, the incoherent space charge tune spread can reach values up to $\Delta Q = -0.5$ [7]. The systematic resonances at the integer tunes $4Q_{x,y} = 16$ are strongly excited by the space charge potential due the lattice periodicity of 16, in combination with all other random field errors. To avoid beam degradation due to the integer resonances, the machine is operated very close to the vertical half-integer resonance $2Q_y = 9$. Operation with working points close to the half-integer resonance strongly enhances the β function distortions, which can eventually lead to beam losses. Studies showed that two of the main defocusing quadrupoles of the machine (QDE3 and QDE14) are optimal for compensating the perturbations caused by the injection chicane and for this reason they have been equipped with additional, individually controlled power supplies [8].

SIMULATIONS OF THE PSB INJECTION CHICANE OPTICS PERTURBATIONS

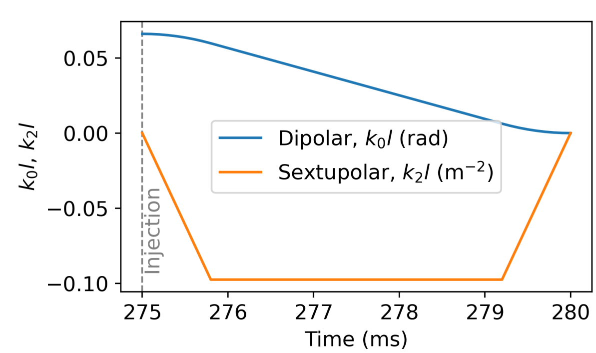

Figure 1: Modelled dipolar (blue) and sextupolar (orange) component of the BSWs.

The edge effects and the sextupolar components generated by eddy currents have been modelled in MAD-X [9] and applied in the PSB lattice. Figure 1 shows the expected dipolar and sextupolar component at one of the BSW magnets. The

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chicane fully collapses 5 ms after the injection, which itself happens 275 ms after the start of the PSB magnetic cycle.

The edge focusing and the feed-down effects induce a β-beating in the vertical plane, which is defined as:

$$\frac{\delta\beta_y}{\beta_y} = \frac{\beta_y - \beta_{y,0}}{\beta_{y,0}}, \qquad (1)$$

where $\beta_{y,0}$ is the nominal β-function around the machine. The injection perturbations change dynamically during the collapse of the chicane, leading to a dynamic change of the vertical β-beating, as shown in the top plot of Fig. 2. Because of that, time dependent compensation strengths are needed to be applied in QDE3 and QDE14 during these 5 ms. At the injection time ($t = 275$ ms), the chicane is at its maximum amplitude and the perturbation is the strongest with the expected maximum β-beating reaching 45% for a vertical tune of $Q_y = 4.44$. For tunes closer to the half-integer resonance, the maximum β-beating can exceed 200%. The tune distortions coming from the injection chicane are of the order of $3 \cdot 10^{-2}$ for the vertical plane.

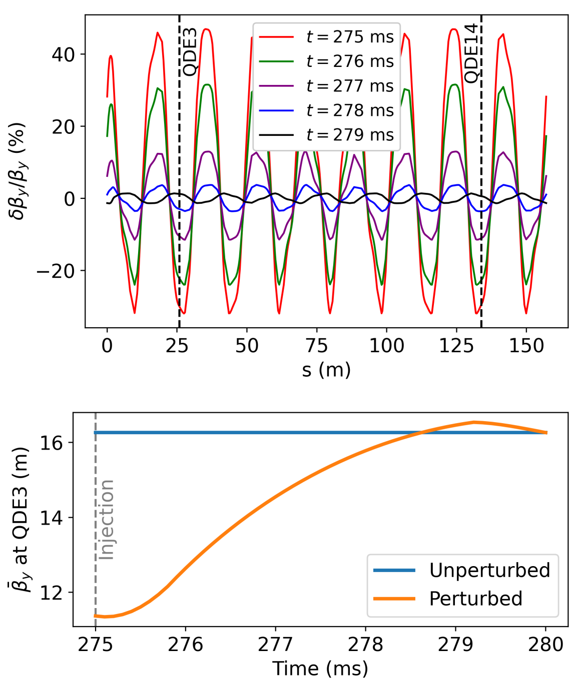

Figure 2: Expected β-beating around the ring for different times in the cycle (top) and optics distortion at the position of QDE3 (bottom).

The bottom plot of Fig. 2 shows a simulation of the expected distortion in the spatial average $\bar{\beta}_y = \int \beta_y(s)\, ds$ inside the QDE3 as a function of time. The unperturbed $\bar{\beta}_y$ (blue line) is 16.26 m. Due to the injection chicane perturbations, the β-function is deformed (orange line). The deformation is similar for the QDE14 magnet. The injection chicane β-beating is compensated by correcting the local β function distortions at the position of these two quadrupoles.

To identify the induced distortion in the β-function at the positions of QDE3 and QDE14, the k-modulation method is used. This method consists of applying a small quadrupolar kick (δk) to the beam, and measuring the induced tune shift (δQ), which depends on the β-function at the position of the quadrupole. In the region close to the half-integer resonance and in first order approximation in δk, this tune shift is given by [10]:

$$\delta Q = \frac{1}{2\pi}\cos^{-1}\left(\cos(2\pi Q_0) + \frac{\bar{\beta}\delta k L}{2}\sin(2\pi Q_0)\right) - Q_0, \qquad (2)$$

where Q_0 is the nominal betatron tune, L is the quadrupole magnetic length and $\bar{\beta}$ is the spatial average β-function along the quadrupole. Simulations showed that by using k-modulation, the distortion in the β-function at QDE3 and QDE14 can be determined very accurately.

The measured distortions in the β-functions are used to compute the dynamic β-beating correction from a predefined response matrix. This response matrix is generated in MAD-X by installing focusing errors around the injection region of the PSB lattice, to mimic the induced β-beating of the injection chicane, and then by matching the optics using the focusing strength of QDE3 and QDE14. This process is repeated for a wide range of working points and for different focusing errors. The β-functions measured with k-modulation are interpolated to the response matrix to find the optimal configuration for the strengths of QDE3 and QDE14 that will minimize the β-beating. In a similar way, dynamic correction values that are applied to all the PSB focusing and defocusing quadrupoles are also extracted from the response matrix, in order to compensate the tune perturbations due to the injection chicane.

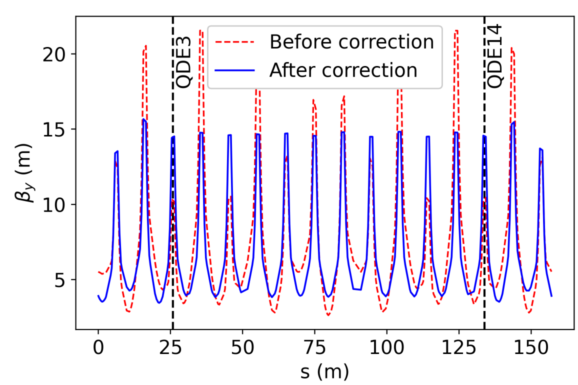

Figure 3: Simulated β-function before and after applying the correction at $t = 275$ ms for a working point of $(Q_x, Q_y) = (4.39, 4.44)$.

A simulation of the k-modulation measurement was performed and the dynamic β-beating correction was calculated and applied to the PSB lattice, with the model injection chicane perturbation. The result was the decrease of the injection chicane β-beating to values less than 1% (RMS). The simulation was repeated for various vertical tunes and the results were equally good, even when including the dynamic tune correction, which slightly degraded the β-beating correction. This showed that, for the case of the PSB, the method

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works in principle very well. Figure 3 shows an example simulation of the perturbed and the corrected vertical β-function around ring 3 of the PSB for the working point of $(Q_x, Q_y) = (4.39, 4.44)$. With this method, some unavoidable residual β-beating around the injection region is present, which is nevertheless small.

A series of simulation studies followed in order to investigate the robustness of the k-modulation-based correction method, when considering uncertainties that are expected to be present in the actual machine. These include uncertainty in the tune measurement, presence of random focusing errors other than the injection chicane, space charge effects and calibration errors. In all cases, the k-modulation-based correction method managed to maintain the RMS β-beating levels on average below 6 % [11, 12], which was considered acceptable.

β-BEATING MEASUREMENT AND CORRECTION AT THE INJECTION OF THE PSB

During the PSB commissioning after the LIU upgrade, the β-beating was measured at the positions of QDE3 and QDE14 for all rings using the k-modulation technique, with an operational application developed for this purpose [13].

The quadrupole setting was static, in the sense that a single shift in the strength (δk) was programmed for the full duration of the chicane. The quadrupole strength was changed for QDE3 and QDE14 individually in order to avoid any tune shift dependence on the relative phase advance between the two quadrupoles.

For a particular k-setting, the tune was measured multiple times during the PSB cycle. The tune measurement is performed by exciting the beam with the transverse damper applying a frequency chirp and recording the turn-by-turn data through a Base-Band-tune pickup (BBQ system). By applying a Fast Fourier Transformation to this BPM signal over many turns, the fractional tune of the beam is extracted. Due to the frequency chirp excitation, the minimum number of turns that can be recorded with this method in the PSB is 1024, which corresponds to approximately 1 ms, at injection energy. This limits the tune measurement to only five times during the fall of the injection chicane. Furthermore, during these 1 ms intervals, the β-beating changes considerably, and so the uncertainty in the calculated β-functions is expected to be relatively large.

Multiple cycles with different k-settings are necessary for the β-beating measurement. The PSB is a fast-cycling accelerator with a basic period of 1.2 s. The different cycles are independent from each other and follow a predefined supercycle which is repeated continuously (pulse-by-pulse modulation). This allowed the use of hundreds of cycles within a reasonable time for collecting the data. The measurement process was automated with the k-modulation application.

Figure 4 shows the reconstruction of the vertical β-functions at QDE3 of ring 3 by fitting the measured $(\delta k, Q_y)$ pairs with Eq. (2). The different colors correspond to different times during the fall of the chicane. The fluctuation of the tune measurement is of the order of $5 \cdot 10^{-3}$, and thus more than 100 different cycles, i.e. different k-settings, are needed to get a precision in the β-function of less than 0.2 m. The programmed vertical tune is constant at the value of $Q_y = 4.44$, but at $\delta k = 0$ the actual tune is perturbed due to the focusing errors from the injection chicane. Beam losses start to appear for vertical tunes higher than $Q_y = 4.45$. The results are similar for the quadrupole QDE14, and all rings.

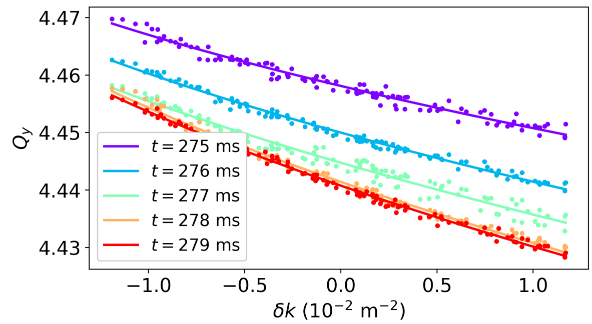

Figure 4: K-modulation data for ring 3 of the PSB. Each color corresponds to a different time of the cycle after injection.

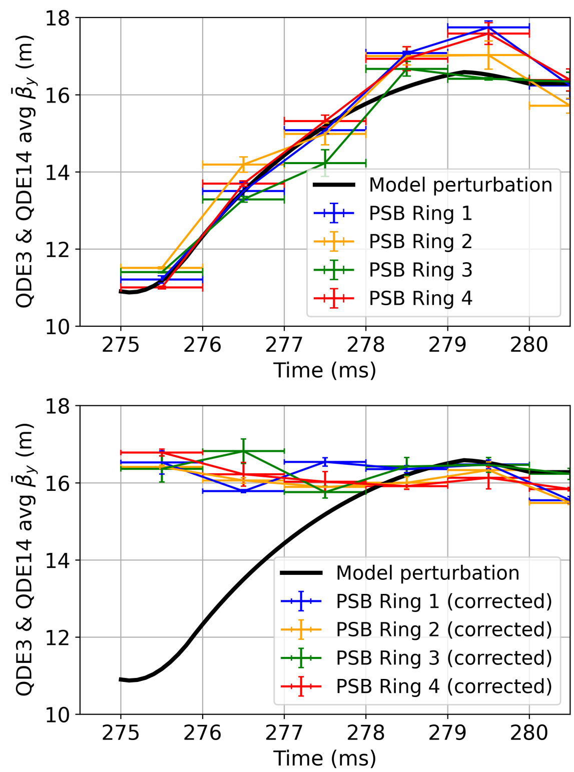

Figure 5: Measured $\bar{\beta}_y$ values (averaged between QDE3 and QDE14) before (top) and after (bottom) applying the dynamic injection chicane β-beating correction

The top plot of Fig. 5 summarizes the average β-function at the positions of QDE3 and QDE14 for all rings as a function of time for the first 5 ms after injection. The black

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line represents the distortion due to the injection chicane perturbations, as expected from the model of Fig. 1 and was extracted from the simulations at the working point of $(Q_x, Q_y) = (4.39, 4.44)$, for which the measurements were performed. After $t = 280$ ms, the chicane is being fully collapsed and so the β-function remains constant and equal to the unperturbed value, which is 16.26 m.

The agreement between the expected and the measured perturbation is excellent, which suggests that there is a good modelling of the injection chicane error sources and the machine lattice. Some ring-to-ring differences are also observed, with the external rings appearing to have larger than expected values for the β-beating between 278 ms and 280 ms where the sextupolar component is more dominant than the edge focusing. This could be caused by stronger eddy currents at the magnets of these rings, but further investigations are needed to confirm this.

The measured β-beating at the locations of QDE3 and QDE14 was then interpolated to the response matrix and the dynamic β-beating correction was calculated and applied to these two quadrupoles. Furthermore, the tune perturbations caused by the injection chicane were also improved by applying additional corrections to all the focusing and defocusing quadrupoles of the PSB.

The β-beating was then once more measured, in a similar way as before, and the result is shown in the bottom plot of Fig. 5. It can be observed that the vertical β-functions are roughly constant, with values very close to the unperturbed value, throughout the entire duration of the chicane decay. This clearly shows the effectiveness of this approach for the minimization of the β-beating around the machine. Another set of measurements was followed in order to calculate and apply a second iteration of correction functions, but this did not give noticeable improvements.

The β-beating correction functions have been calculated for a specific working point. Measurements and simulations show that for small tune changes, the sensitivity of the correction on the exact tune is not significant [14]. Thus, the same dynamic β-beating correction has been used for all vertical tunes up to $Q_y = 4.47$ and only the tune correction has been adjusted accordingly for each working point. In order to approach even closer to the half-integer resonance and eventually cross it, the injection chicane perturbation must be corrected iteratively, along with the correction of the half-integer resonance excited by error sources other than the injection chicane.

IMPACT ON BEAM PARAMETERS

The need for the PSB to operate close to the half-integer resonance is due to the fact that the beams at injection energies suffer from a large space charge tune spread. Above a certain intensity, particles from the beam core reach the strong resonances at the integer tunes $Q_{x,y} = 4.0$ causing an increase in the emittance. By moving the working point further away from the integer, i.e. closer to the half-integer resonance, the emittance increase for the same intensity becomes smaller. Thus, larger intensities can be accumulated for the same emittance, resulting in a beam with a higher brightness.

Intensity

In order to observe the effect of the corrected β-beating, the beam intensity was measured at injection for different vertical betatron tunes. In the PSB, the beam intensity is measured with Beam Current Transformers [15]. Figure 6 shows the beam intensity for different vertical tunes with (green bars) and without (red bars) the β-beating correction. For tunes far from the half-integer resonance, the effect of the correction is insignificant. When approaching the half-integer resonance, if the β-beating is not corrected, more than 25% of the beam intensity is lost at the vertical tune of $Q_y = 4.46$, while the beam is completely lost for $Q_y = 4.47$. With the correction enabled, the beam fully survives for tunes much closer to the half-integer resonance at $Q_y = 4.5$. Up to the present moment, for tunes above $Q_y = 4.47$ the beam is lost in all cases. The results are similar for higher intensities.

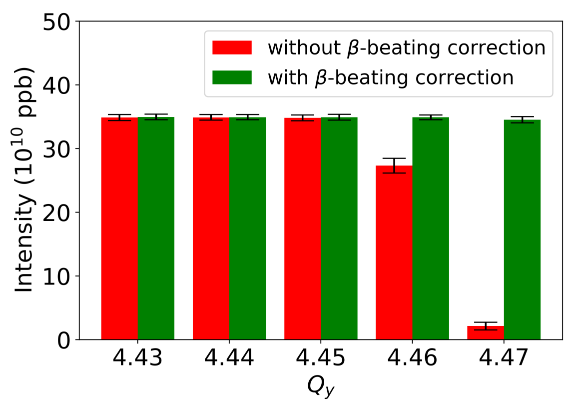

Figure 6: Intensity with (green) and without (red) the injection chicane dynamic β-beating and tune correction applied as a function of the vertical tune.

Emittance

The emittance was also measured for various vertical tunes at flat-top energy, before extraction. The transverse beam profiles were measured with a wirescanner (WS) [16]. For the calculation of the emittance, the model β-function and the dispersion were assumed, while the momentum spread ($\delta p/p$) was measured using longitudinal tomography [17]. A Gaussian fit was applied to all profiles. The measurements were performed with a beam close to the LIU intensities (approximately $300 \cdot 10^{10}$ ppb) at which the interaction of the beam with the resonances is enhanced.

Figure 7 shows the horizontal (top) and the vertical (bottom) emittance for three vertical tunes, with and without the β-beating correction enabled. In the horizontal plane, the emittance remains constant between 1.8 to 1.9 µm·rad, as expected. In the vertical plane, the emittance becomes

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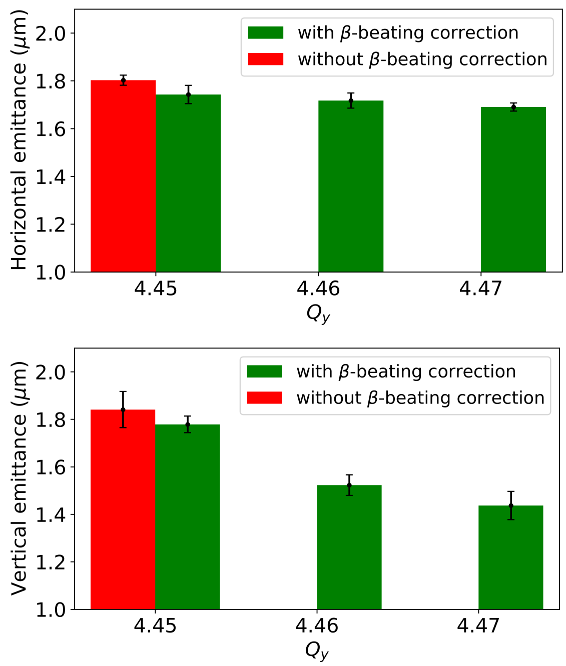

Figure 7: Horizontal (top) and vertical (bottom) emittances as a function of the vertical tune close to extraction (t = 770 ms). The emittances without the β-beating correction are shown only for Q_y = 4.45, since for the other vertical tunes there are significant losses which distort the profiles.

smaller when moving away from the integer resonance. For this particular intensity, for a tune increase of 0.02, the emittance decreased by approximately 0.2 µm·rad. The effect is less pronounced for lower intensities.

It is important to mention that non-Gaussian overpopulated tails are observed in the vertical beam profiles of the beam and their origin is not yet fully understood.

Brightness

In the PSB, the figure of merit which characterizes the performance of the LHC beams is the beam brightness, defined as the ratio of the intensity over the emittance.

Figure 8 summarizes recent brightness measurements for different configurations and compares them with the brightness curve before the LIU upgrades (orange), for which at an intensity of $300 \cdot 10^{10}$ ppb the emittance is approximately 3.5 µm. The data presented in blue were acquired after the LIU upgrades, during the initial phase of the beam commissioning, when the injection chicane β-beating correction, the resonance compensation schemes and the tune evolution were not yet fully optimized. The beam brightness in this initial phase was already very close to the LIU specifications, with an emittance of 1.8 µm for an intensity of $300 \cdot 10^{10}$ ppb. The latest results, including the injection chicane beta-beating correction, the optimised compensation schemes of the third and fourth order resonances [18], and the working point and tune evolution optimisation, are shown in green. In the latest case, the brightness can exceed the LIU target (black dashed line), as was expected from the simulations [19]. At an intensity of $300 \cdot 10^{10}$ ppb, the emittance is smaller by approximately 0.2 µm compared to the data of early 2021.

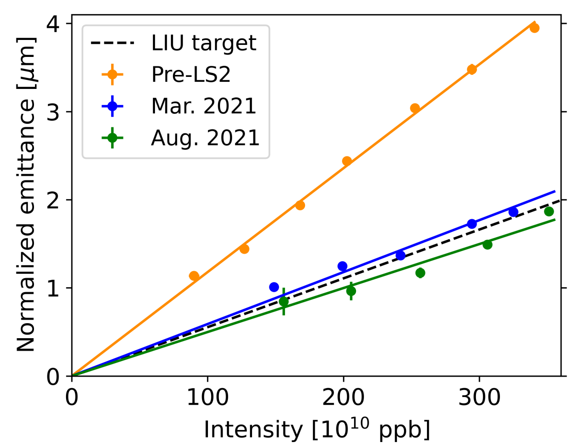

Figure 8: PSB brightness curves in ring 3.

Although the first results are encouraging, the work to optimize the correction of the focusing perturbations to raise the vertical tune above the half-integer resonance in order to further improve the beam brightness is still ongoing.

CONCLUSIONS AND OUTLOOK

A strong vertical β-beating is induced by the magnets of the H^- injection chicane after the LIU upgrades in the PSB. A method to identify and correct this β-beating was presented. This method consists of using k-modulation to measure the induced optics distortion at the positions of two individually powered quadrupoles and then to interpolate these values to a model-based response matrix. The method was employed during the PSB beam commissioning after the LIU upgrades. The injection chicane β-beating was measured at the expected levels and then corrected using the defocusing quadrupoles QDE3 and QDE14. The correction allowed a stable operation of the beam with working points closer to the half-integer resonance $2Q_y = 9$. This mitigated the interaction of the beam with the systematic resonances of the PSB at the integer tunes ($4Q_x = 16$ and $4Q_y = 16$) through the space charge tune spread, thus reducing the emittance and increasing the brightness of the LHC beams.

Optimization studies are ongoing to address the origin and the evolution of the non-Gaussian tails observed in the vertical beam profiles, the impact of the chromaticity correction and the injection above the half-integer resonance without considerable beam degradation.

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