OPTICS MEASUREMENTS IN THE CERN PS BOOSTER USING TURN-BY-TURN BPM DATA

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Abstract

As part of the LHC Injector Upgrade Project the injection of the CERN PS Booster will be changed to increase intensity and brightness of the delivered beams. The new injection scheme is likely to give rise to beta beating above the required level of 5% and new measurements are required. Achieving accurate optics measurements in PSB lattice is a challenging task that has involved several improvements in both hardware and software. This paper summarizes all the improvements that have been performed in the optics measurement acquisition system together with a brief summary of the first results obtained.

INTRODUCTION

Several major changes will be performed in the PSB within the LHC Injector Upgrade project (LIU) [1, 2]. PSB is composed of four superimposed rings with the same nominal optics. We performed measurements in all 4 rings, but limit this report to Ring 1 only because the results for all rings are similar. Linac4 will accelerate H^- ions instead of protons that were delivered by the decommissioned Linac2. The new injection scheme is based on the charge-exchange injection principle [3, 4] that requires an orbit bump during the injection process. It will modify the optics due to edge focusing of the bending magnets creating the bump and eddy currents induced in the vacuum chamber during the bump collapse. This perturbation becomes very important for the highest intensity beams, for which the working point at injection needs to be just above the half-integer tune due the larger tune-spread that can exceed 0.5. This requires minimization of the half integer resonance driving term, and therefore a good control of the beta functions.

In preparation for the commissioning in 2020, the acquisition and control systems, as well as the analysis tools, have been upgraded to increase accuracy of the optics measurements and corrections. The techniques and the tools developed for the LHC [5] were fully adapted for the PSB. They reconstruct the optical β-functions from frequency analysis of turn-by-turn (TbT) beam position monitor (BPM) data using two methods [6–8]. The first one, which is known as N-BPM method [9, 10], computes β from measured phase advances between BPM pairs ($\phi_{x,y,ij}$). Subscripts x,y were added to denominate horizontal and vertical plane, respectively. The second one uses the amplitude of the oscillations [11]. We refer to the β values from the respective methods as β^{ϕ} and β^{A}.

Betatron oscillations are excited simultaneously in both horizontal and vertical planes using kicker magnets. The excitation can be applied either over a single turn if the kicker magnet is ramped up and down within one turn or it can be a continuous modulation close to the betatron frequency powering the kicker sinusoidally with the aid of an external function generator. The latter is referred to as AC dipole (ACD). In the PSB, ACD is implemented using the transverse feedback system (TFB or ADT [12]) driven by a dedicated waveform generator with a sine signal at a frequency f_{exc}. It is convenient to define $\mathrm{Q}^{\mathrm{D}}_{x,y} = \frac{f_{\mathrm{exc}}}{f_{\mathrm{rev}}}$ so the excitation frequency can be directly compared with the tune. If the excitation is applied punctually, the maximum induced transverse amplitude is limited by the maximum kicker strength. In case of continuous modulation, the amplitude will depend on the angular kick strength, the distance between $\mathrm{Q}^{D}_{x,y}$ and tune $Q_{x,y}$ ($\Delta Q_{x,y} = Q_{x,y} - \mathrm{Q}^{D}_{x,y}$), and the values of the β functions at the AC-dipole [13]. Both, the amplitude of the driven oscillations and the number of recorded turns, have an impact on the Fourier analysis resolution [8]. For excitation with a single kick the number of turns available for the Fourier analysis is limited to several hundreds due to the decoherence effect, which in the PSB can not be corrected with sextupoles simultaneously in both planes. Therefore, the ACD excitation was mostly used in the presented measurements.

The power of the transverse feedback amplifiers has been increased from 100 W to 800 W. However, for the purpose of the optics measurements only half of the maximum power can be used to limit the pollution from higher-order harmonics that reduces the accuracy of the measurements.

Faster analogue-digital converters (ADC) were installed allowing all the BPMs to record data in turn-by-turn mode [14] with a sampling rate 100 times faster that the beam frev. A dedicated application for turn-by-turn data acquisition has been developed for optics measurements. In the previous application, the standard readout system had a position granularity of 0.1 mm, allowing to reduce the amount of transferred data by working with integers. The new application acquires the raw ADC signals, calculates the positions and applies the calibration factors such that the granularity is limited only by number of bits in the ADCs. This improvement has a direct impact on BPM resolution, increasing it from an average of 0.05 mm to 0.03 mm.

The software tools for the LHC optics measurements and corrections were fully adapted for CERN PS and PSB such that turn by turn BPM data can be analyzed in an automatized manner. PSB software improvements consisted of: model creation for the conditions under study, filtering and cleaning of the acquired data [8], optimization of the optics reconstruction algorithms and implementation of so called segment-by-segment analysis that permits to propagate mea-

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sured optical functions to an arbitrary location and to study optics locally within a section of the machine and calculation of optics corrections [15].

Calculation of β^{ϕ} uncertainty, which originally was based on Monte-Carlo simulations [9] was recently replaced by analytic formulae [10]. As an input it requires estimates of the systematic errors present in the lattice. Unfortunately, complete magnetic measurements of the magnets were never done, so precise numbers are not available. Uncertainty of the normalized gradient was set to $2 \cdot 10^{-4}$ and $1 \cdot 10^{-4}$ in the focusing and defocusing quadrupoles, respectively, which are rather optimistic estimates. For the longitudinal BPM misalignments the most recent measured offsets were used ranging from 1 to 10 mm [16].

MEASUREMENTS

The accuracy of β^{ϕ} measurement in the PSB is heavily limited by the way the BPMs are distributed in the lattice. The rings are divided into 16 equal cells, each of them is composed of two bending magnets with a quadrupole triplet in between [17–19]. There is only one BPM per cell, located after the first focusing quadrupole. At injection, the nominal working point is set to Q_x=4.28, Q_y=4.30. Tune values are adjusted to higher values when the injected beam intensity increases. The location of the BPMs combined with the values of the tune lead to a phase advance between consecutive BPMs close to 90°. This introduces large uncertainty in the β-function due to the sensitivity of the β^{ϕ} to $\phi_{x,yij}$ fluctuations near $\Delta\phi_{x,yij} \approx \frac{\pi}{2}$ [9].

It is well known that β^{A} accuracy is limited by the precision of BPM calibrations. An optics-measurement-based-BPM-calibration, previously used in the LHC [11], has been explored for the PSB by measuring β functions at an alternative working point, where β^{ϕ} can be used as a reference. These are then used in the nominal optics measurement, performed right after the calibration with similar conditions, namely, beam intensity and BPM gain setting.

Beam was injected from Linac2 at 50 MeV and accelerated to 160 MeV, which corresponds to the new injection energy with Linac4. For the initial measurements performed after the implementation of the hardware and software upgrades, the beam response was not as expected showing very uneven amplitude patterns for both ACD and kicker excitations. It was understood that the nominal beams with the nominal intensities became unstable when excited. The bunches were elongated by lowering the RF voltage and applying a second harmonic. Similarly, chromaticity, linear coupling and tunes were optimized for stability.

Beam response has been better controlled by adjusting the distance between the driven and beam tune $\Delta Q_{x,y}$. Measurements parameters were optimized to maximize accuracy of phase, and therefore β function measurements. Several iterations on beam parameters, exciters configurations, and BPM settings have been tested covering a range of intensities from $10 \cdot 10^{10}$ to $140 \cdot 10^{10}$ ppb, a range of driven tunes and different settings of the BPM readout. The beam intensity was optimized to achieve stable conditions with $140 \cdot 10^{10}$ protons per bunch (ppb).

The amplitude of the driven oscillations is proportional to $\frac{1}{|sin(\pi\Delta Q_{x,y})|}$ [17]. Smaller values of the $\Delta Q_{x,y}$ introduce larger excitation, but can eventually trigger a resonance if $\Delta Q_{x,y} = 0$. In practice the minimum distance depends on the tune stability.

Optimal beam intensity should be below $200 \cdot 10^{10}$ ppb to avoid irregular beam response to ACD [20] and above 10^{10} ppb, to ensure good BPM resolution. Final parameters used during 2018 optics measures were: beam intensity of $140 \cdot 10^{10}$ ppb and a $\Delta Q_{x,y} = \pm 4 \cdot 10^{-3}$.

A dedicated optics was commissioned with horizontal and vertical tunes respectively of 3.38 and 5.42. The optics name is based on the integer tune values, namely Q3Q5, while the nominal one is Q4Q4. In the Q3Q5 optics the phase advance is moved further away from the inconvenient $\frac{n\pi}{2}$. In the horizontal plane, the phase advance changes from 0.53π to 0.42π, while in the vertical plane it moves from 0.52π to 0.68π. Optics measurements were performed for both, Q3Q5 and Q4Q4, for all rings.

Table 1: Summary of phase-advance error in 2π units measured in September and October in Ring 1 for the working point Q3Q5 and Q4Q4.

	r.m.s ($\sigma(\phi_{x,ij})$)		r.m.s ($\sigma(\phi_{y,ij})$)	
	Sept.	Oct.	Sept.	Oct.
Q3Q5	$3 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
Q4Q4	$1.5 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$

Beam stability studies were done by analyzing phase-advance correlation with oscillation amplitude and their spreads. We found that the spread was dominated by the machine fluctuations rather than by a too small signal to noise ratio (insufficient excitation amplitude and/or BPM resolution). Table 1 summarizes the rms phase advance error between all pairs of consecutive BPMs ,($\sigma(\phi_{x,y,ij})$), defined as the standard deviation for consecutive beam excitations. for both working points for two data sets acquired before stability optimization (September) and after the beam stability optimization (October). Last measurements, performed in October 2018, show an improvement in the phase uncertainty allowing better β-function reconstruction in both working points. From Table 1 it also can be seen that the larger phase advance is due to the lack of stability of Q3Q5 optics.

The BPM system has a built-in functionality to perform detailed calibration using a reference signal. As the BPM reference calibration system had not been fully commissioned, theoretical calibration values were used. In 2017 these values were recomputed and the same value was set for all BPMs. By comparing β^{ϕ} and β^{A} measured with Q3Q5 optics it has been confirmed that the calibration is not constant among all BPMs. Deviations up to 15% with respect to the nominal calibration factor has been observed, especially

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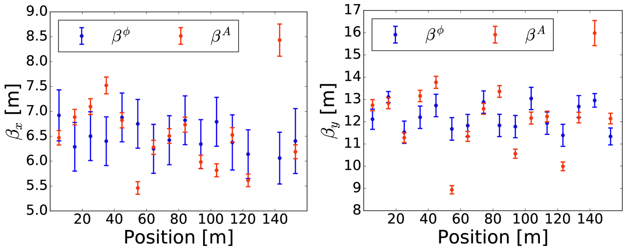

Figure 1: Measured β^ϕ and β^A functions for the Q3Q5 optics as a function of position: horizontal (left), vertical (right).

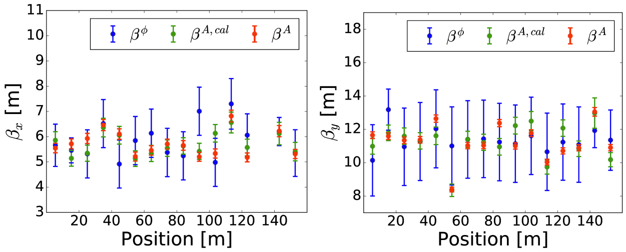

Figure 2: Measured β^ϕ, β^A and $\beta^{A,cal}$ functions for the Q4Q4 optics as a function of position: horizontal (left), vertical (right). BPMs connected to the radial feedback have not been calibrated due to the noise introduce in the turn-by-turn measurement.

for the BPMs connected to the radial feedback that acts as an extra source of BPM noise, affecting the quality of the measurements. Its effect in the optics measurements is more pronounced in the Q3Q5 working point, where the beam is less stable. Therefore, to avoid introducing extra noise in the Q4Q4 optics, calibration factors obtained for BPMs number 4, 6, 12 and 14, which are connected to the radial feedback, have not been propagated to the Q4Q4 optics.

Figure 1 shows a comparison between the β^ϕ and β^A measured in Q3Q5. These values were used to compute the calibration factors for each individual BPM [11]. Figure 2 shows a comparison of the optics measured with Q4Q4 optics using β^ϕ, β^A and $\beta^{A,cal}$, obtained by applying the measured calibration factors as the β ratios from Fig. 1.

Analyzing $\sigma(\beta^\phi_{x,y})$ in Figs. 1 and 2 it can be seen that the β^ϕ obtained in Q3Q5 is much more accurate than for the Q4Q4 optics. The values of the $\sigma(\beta^\phi_{x,y})$ for the two optics configurations is summarized in Table 2. This is due to the much smaller systematic error from the more favorable phase advance. Table 2 summarizes the r.m.s. β-beating, relative difference between the measured β and the β given by the MADX model, and the average β-error $\sigma(\beta)$. The increase in the error bar of $\beta^{A,cal}$ is due to the error propagation of the calibration factors. Using $\beta^{A,cal}$ allows to reduce the uncertainty in the Q4Q4 optics from 15% to 9% in the horizontal plane and form 19% to 8% in the vertical one.

The segment-by-segment algorithm has been implemented using as boundary conditions the β^ϕ and the $\beta^{A,cal}$. Twiss α parameter is also needed to propagate β-functions measured in a BPM to another element, e.g, the wire scanners. However, α is currently only computed using $\phi_{x,y,ij}$ and its large relative error bar is directly propagated to the β calculation. A new algorithm for α calculation using β^A at neighbouring BPMs and model transfer matrix between them was tried without improving its resolution.

Table 2: Summary of r.m.s β-beating measured in Ring 1. The r.m.s. β-beating is defined as $(\beta^{\text{meas}} - \beta^{\text{MADX}})/\beta^{\text{MADX}}$ where β^{meas} refeers to the β measured using three different approaches: $\beta^\phi, \beta^A, \beta^{A,\text{cal}}$ together with its associated error bars.

	Horizontal			Vertical		
	β^ϕ	β^A	$\beta^{A,\text{cal}}$	β^ϕ	β^A	$\beta^{A,\text{cal}}$
r.m.s. $(\frac{\Delta\beta}{\beta})$%	13	10	8	6	9	9
average $(\sigma(\beta))$ %	15	3	6	19	2	4

CONCLUSIONS

Implementation of a new optics-measurement-based-BPM-calibration approach has been a big motivation for improvements in the data acquisition system. Hardware improvement allowed to increase the peak-to-peak amplitude of excited betatron motion without changing the $\Delta Q_{x,y}$. The LHC software tools for optics measurements and corrections [21] were adapted for the PSB and now the process is fully automatized, speeding up the time needed for optics commissioning and studies. The main contribution of the $\sigma(\beta^\phi)$ comes from the value of the $\phi_{x,yij}$ close to $\frac{n\pi}{2}$ and not for its accuracy $\sigma(\phi_{x,yij})$. The hardware and beam stability improvements have led to a smaller r.m.s. phase advance uncertainty as shown in Table 1. The good $\phi_{x,yij}$ accuracy, less than 1% relative error, allows to use this observable for optics corrections [21]. Finally, the implementation of the segment-by-segment technique allows to evaluate the β-function at the wire-scanner positions [22]. Nonetheless, the large α uncertainty propagates to the β-calculation, exceeding the required uncertainty.

Clearly, installation of additional BPMs would resolve this issue, however, it is very difficult to find space in the lattice. Currently usage of other already installed pick-ups is being studied to provide additional turn-by-turn position information, for example the tune monitors. It is also planned to study another optics measurement method that combines Orbit Response Matrix with phase advance information provided by the turn-by-turn analysis, which was successful in improving the resolution in ESRF [23].

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