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MATCHING STUDIES BETWEEN CERN PSB AND PS THROUGH MULTI-TURN BEAM PROFILE ACQUISITIONS

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) project, the investigation and quantification of the optics mismatch between the CERN Proton Synchrotron Booster (PSB) and PS is a crucial step in understanding the source of horizontal emittance growth between the two machines. Extensive studies were carried out to estimate the mismatch from single-pass measurements in the transfer line and to rematch the transfer line to reduce the dispersive mismatch at PS injection while keeping the betatron matching unaltered. This paper presents the results of the data analysis of more recent multi-turn measurements, which profited from a new turn-by-turn beam profile monitor in the PS ring, to assess the achieved level of matching and corresponding emittance growth. The results confirm the improved matching and demonstrate the feasibility of the multi-turn technique as a fundamental tool that will be important for the recommissioning of the renovated transfer line after Long Shutdown 2.

INTRODUCTION

In addition to the increased PS injection energy from 1.4 to 2 GeV, the baseline beam parameters [1] foreseen by the LIU project require a larger longitudinal emittance at transfer from the PSB to reduce the effects of space charge as the beam brightness is increased. The increased momentum spread will exacerbate the existing dispersion mismatch already suspected as driving horizontal emittance growth at injection [2] on today's operational (OP) BCMS (Bunch Compression, Merging and Splitting) LHC beam [3]. In mitigation, the injection transfer line is undergoing upgrade to largely remove the mismatch in the horizontal dispersion. Nevertheless, studies have hastened to understand the discrepancy between the predicted and measured horizontal emittance growth on the OP beam, discussed at length elsewhere in these preceedings [4]. In short, the expected emittance growth from dispersion mismatch of the beam envelope is ~ 15% for an rms, normalised emittance of 1 mm mrad delivered from the PSB, however, measurements with the wire scanners in the PSB and PS have indicated much larger values closer to 50% in operation.

Until recently it was not possible to observe the fast, turn-by-turn beating of the beam size during the filamentation process immediately after injection. This made it difficult to unambiguously identify and quantify the emittance blow-up from dispersion and betatronic mismatch. For the purposes of the matching studies, a rematched transfer line optics, referred to hereafter as ReM, with an improved dispersion and betatronic matching, was implemented and tested using Ring 3 of the PSB only. The details of the prerequisite transfer line matching studies can be found summarised in [2]. The present work does not yet address intensity dependent effects or any additional emittance growth due to space charge. The work presented in this paper echoes many of the studies carried out almost 20 years ago in preparation for LHC commissioning [5, 6].

MEASUREMENT PROCEDURE

The PS machine was set-up with the newly deployed and operational LIU BCMS cycle employing low chromaticity to combat the increased chromatic tune spread from the future larger longitudinal emittance [7]. Linear coupling is corrected using the available skew quadrupoles requiring the transverse feedback (TFB) system to stabilise the beam against head-tail instabilities on the injection plateau. The tunes were set-up to ($Q_x = 6.21$, $Q_y = 6.24$) and the injection oscillations kept below ±0.5 mm with the TFB on. The PS RF system was switched off to ensure the phase loop played no role after injection. The turn-by-turn profiles were acquired on a wire grid (BSG) directly intercepting the beam and located in straight section 52. The grid, equipped with a new fast readout system, has 30 wires in each plane with a pitch of 1 mm on the inner 12 wires and 2.5 mm on the remaining outer wires. An important aspect of the procedure was to ensure that the wires on the grid were not damaged by the beam circulating in the machine. The number of turns that a given beam could safely circulate after injection was specified in terms of its brightness and intensity [8], which conservatively limited the BCMS beam from a single ring and with an intensity ranging from approximately $50 - 90 \times 10^{10}$ protons to ~ 30 turns. After the permitted number of turns multiple and redundant kicker systems were programmed to reliably destroy the circulating beam by pushing it onto the machine's aperture [9].

Beam Profile Analysis

The turn-by-turn readout of the wire grid was fitted with a 5-parameter Gaussian fit function including a linear baseline correction to extract the average beam size and position. The beam size n turns after injection can be written as the quadratic sum of independent and Gaussian betatronic and dispersive contributions in the presence of injection mismatch as shown in Eq. (1), see [5], where q_x is the horizontal fractional tune, ϵ_x is the injected horizontal rms geometric emittance, σ_p/p is the rms momentum spread in the beam and β_x is the matched Twiss function at the given location in the ring. An additional term is added in quadrature to account for the turn-by-turn interaction of the beam with the

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$$\frac{\sigma_x^2(n)}{\beta_x} = \frac{\epsilon_x}{2}\left(\left(M_g + \frac{1}{M_g}\right) + \left(M_g - \frac{1}{M_g}\right)\cos(\phi + 4\pi(n-1)q_x)\right) + \left(\frac{\sigma_p}{p}\underbrace{(\bar{D}_{0,x} + M_{D,x}\cos(\theta + 2\pi(n-1)q_x))}_{\bar{D}_{0,x}(n)=D_{0,x}(n)/\sqrt{\beta_x}}\right)^2 + \frac{\sigma_{BSG}^2}{\beta_x} \quad (1)$$

wire grid and written as,

$$\frac{\sigma_{BSG}^2}{\beta_x} = \beta_x \Delta x'^2_{\text{rms}}\left(\frac{n-1/2}{2} - \frac{\sin(2\pi(2n-1)q_x)}{4\sin(2\pi q_x)}\right), \quad (2)$$

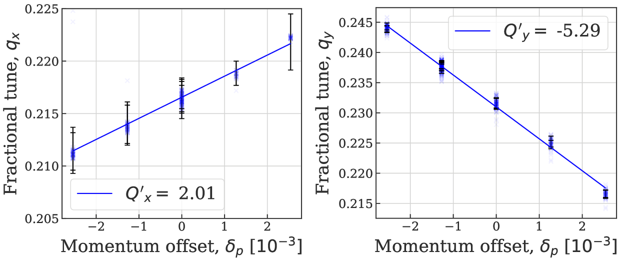
where $\Delta x'_{\text{rms}}$ is the single-pass scattering angle imparted on the beam. In the PS, the matched horizontal lattice functions (β_x = 11.9 m, $D_{0,x}$ = 2.7 m) at BSG52 lead to a beam envelope that is roughly equally composed of betatronic and dispersive contributions for the operational BCMS beam where $\sigma_p/p = 0.9 \times 10^{-3}$. M_g and M_D are the geometric and dispersion mismatch factors, respectively, which quantify the level of mismatch of the incoming beam and the consequential emittance blow-up. The terms ϕ and θ denote the phase advance to the given observation point for the betatronic and dispersive beating, respectively. The analytic results can be found derived in [5]. Neglecting the influence of space charge, it is worthwhile pointing out that a predominant betatronic mismatch would imply an envelope oscillation at a frequency of $f_\sigma = 2q_x$, whereas a predominant but small dispersive mismatch, i.e. $M_D/\bar{D}_0 \ll 1$, would see $f_\sigma = q_x$. For a larger dispersion mismatch the non-vanishing $\cos^2(2\pi q_x)$ term would induce an oscillation at $f_\sigma = 2q_x$ with the potential of masking betatronic mismatch depending on the values of θ and ϕ.

TUNE AND CHROMATICITY

The tune was measured during the first turns by performing a Discrete Fourier Transform (DFT) on the turn-by-turn beam position data measured using both the BSG52 and the capacitive pick-ups of the Beam Position Monitor (BPM) system. The chromaticity was also computed by exploiting the variations of the injected beam momentum offset δ_p applied to measure the dispersion, see Fig. 1. The nominal horizontal and vertical fractional tunes were measured as expected at $q_x = 0.216$ and $q_y = 0.232$, respectively. However, the chromaticities Q'_x and Q'_y were measured at 2.0 and -5.3, respectively, which is roughly a factor two larger than measured later in the cycle. The injection bump has been observed to influence the tune immediately after injection, although further investigations are required to understand its impact on the chromaticity [10].

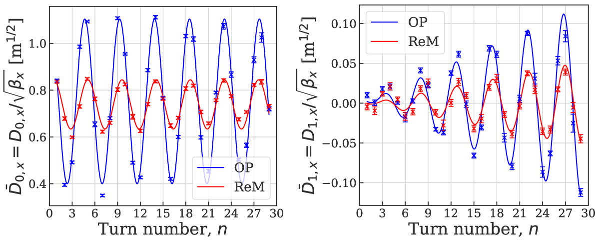
DISPERSION MEASUREMENTS

The dispersion was measured in the first turns after injection using the BSG52 and the BPM system. The estimated error from the covariance of a fitted linear dispersion function was observed to increase with turn number as the dispersion function becomes progressively non-linear. In fact, it was found that the first non-linear correction to the dispersion function, defined in the caption of Fig. 2, grows linearly with the number of turns whilst oscillating with the tune. The dispersion measurements on the BSG52 are presented in Fig. 2 for the different transfer line optics and fitted with their respective harmonic functions. The computed values of M_D from the fitted dispersion beating at all instrumentation devices are summarised in Fig. 3.



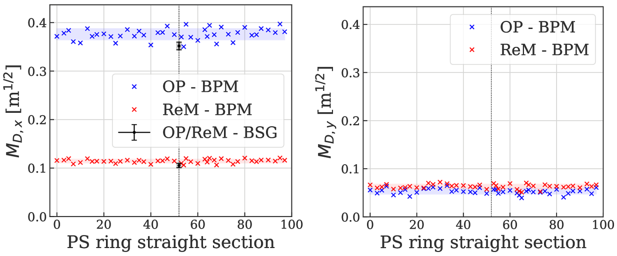
(a) Horizontal (b) Vertical

Figure 1: Chromaticity measurement using all 86 ring BPMs during the first 30 turns.



(a) $\bar{D}_{0,x}(n)$ (b) $\bar{D}_{1,x}(n) \propto n\cos(2\pi n q_x)$

Figure 2: Turn-by-turn non-linear dispersion function, $\bar{D}(n) = \bar{D}_{0,x}(n) + \bar{D}_{1,x}(n)\delta_p$, measured at BSG52.



(a) $M_{x,D,\text{OP}}$ = 0.376 ± 0.012 m$^{1/2}$ $M_{x,D,\text{ReM}}$ = 0.114±0.003 m$^{1/2}$

(b) $M_{y,D,\text{OP}}$ = 0.053 ± 0.006 m$^{1/2}$ $M_{y,D,\text{ReM}}$ = 0.063±0.005 m$^{1/2}$

Figure 3: Measurements of M_D for the OP and ReM optics in the (a) horizontal and (b) vertical planes.

Due to limited beam time available the vertical dispersion could not be measured on the BSG52. The fit parameters ($M_{D,x}$, $\bar{D}_{0,x}$, θ and q_x) measured from Fig. 2 were used to constrain the fitting of the turn-by-turn beam envelope oscillation with Eq. (1) shown in Fig. 4.

PROFILE MEASUREMENTS

The turn-by-turn profile results presented in Fig. 4 show a clear improvement when the rematched transfer line optics is applied, with the dominant envelope oscillation frequency $f_\sigma \sim q_x$. Strikingly, the strongly mismatched beam envelope oscillates at a frequency shifted by 0.03 below q_x. In fact, q_x in Eq. (1) must remain a free parameter to achieve convergence when fitting the analytic expression. The growing amplitude of the envelope with turn number is consistent with the expected emittance growth from scattering on the wires of BSG52 with $\beta_x \Delta x'^2 \sim 0.02\,\mu\text{m}$, along with the development of tails on the profiles. The problematic issue of the large non-Gaussian dispersive component in the beam makes it difficult to reliably extract ϵ_x and σ_p/p from the fit. The frequency components present in the envelope oscillation are summarised in Fig 5(a), where a DFT analysis confirms the improved matching of the beam envelope beating with a frequency closer to the tune and at a significantly reduced amplitude. The limited number of samples (turns) leads to a poor resolution in the DFT and parabolic interpolation [11] around the spectral peak was applied to attain the quoted results. As shown in Fig. 5(b), a strong linear dependence of f_σ with δ_p was observed for the OP optics at twice the measured value of Q'_x. The δ_p dependence for the ReM optics is consistent with the measured Q'_x.

The OP transfer line optics induces $M_D/\bar{D} \sim 0.5$ making it hard to conclude without doubt that there is no betatronic mismatch. Far stronger conclusions can be made for the ReM optics where $M_D/\bar{D} \sim 0.1$ and the betatronic component can be firmly assumed to be negligible.

EMITTANCE BLOW-UP

Significant horizontal emittance blow-up in the PS of $\sim$ 0.33 mm mrad ($\sim$ 30 %) has been measured on the operational BCMS LHC beam with a single bunch from the PSB [4]. The emittance growth after filamentation due to a mismatch in dispersion at injection should scale like,

$$\Delta\epsilon_{x,\text{ReM}} = \left(\frac{M_{D,\text{ReM}}}{M_{D,\text{OP}}}\right)^2 \Delta\epsilon_{x,\text{OP}} \sim \frac{1}{10}\Delta\epsilon_{\text{OP}}. \qquad (3)$$

For the operational BCMS LHC beam ($\sigma_p/p = 0.9 \times 10^{-3}$) this would correspond to a value of $\Delta\epsilon_x = 0.15$ mm mrad reducing to 0.01 mm mrad. Emittance measurements were carried out with a wire scanner 15 ms after injection without any statistically significant change observed. To exaggerate the effect, a BCMS beam with a larger momentum spread ($\sigma_p/p = 1.4 \times 10^{-3}$) was transferred and the emittance growth measured. In this case, the expected emittance growth factor of $(1.4/0.9)^2 \sim 2.4$ with respect to the operational beam was measured at $\sim$ 1.2, regardless of the transfer line optics applied.

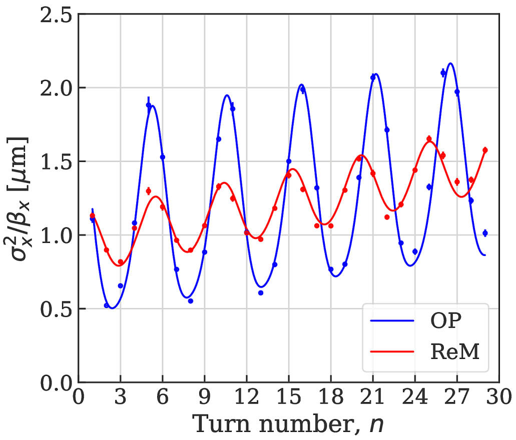
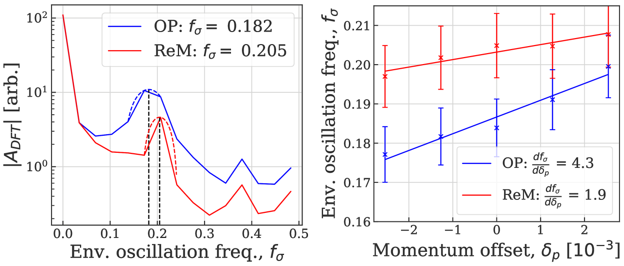


Figure 4: Turn-by-turn beam profile measurements after injection.



(a) DFT with $\delta_p = 0$ (b) $f_\sigma(\delta_p)$

Figure 5: Frequency spectrum of the envelope oscillations in the 30 turns immediately after injection.

CONCLUSION AND OUTLOOK

Turn-by-turn beam profile measurements immediately after injection have confirmed and quantified the dispersion dominated mismatch on the operational LHC BMCS beam as predicted in [2]. The oscillation frequency of the beam envelope in the first 30 turns is depressed compared to the measured fractional tune. Further simulation studies are planned to understand the impact of non-linear dispersion, space charge and changing distributions on the beating of the beam envelope and the emittance growth during filamentation. The shift could be a direct measurement of the effect of space charge [12] and as a next step the data will be compared to the spectra taken with a quadrupolar pick-up [13].

Re-matching of the transfer line made no significant impact on the filamented emittance measured using a wire scanner. Significant efforts are being made to study and quantify the systematic errors in the emittance measurement and to develop the tools needed to effectively de-convolute beam profiles with a large and non-Gaussian dispersive component.

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