ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS087

TRANSVERSE EMITTANCE STUDIES AT EXTRACTION OF THE CERN PS BOOSTER

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Abstract

Transverse emittance discrepancy in the beam transfer between the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS) is observed in operational conditions for the LHC beams at CERN. The ongoing LHC Injectors Upgrade (LIU) project requires a tight budget for beam degradation along the injector chain and therefore the reason for this emittance discrepancy needs to be understood. Systematic measurements have been performed for various beam characteristics (beam intensity, transverse and longitudinal emittance). In this paper, a comparison between the emittance measurements using all available beam instrumentation with different emittance computation algorithms is presented. The results are compared to measurements at PS injection. Furthermore, the impact on the LIU project requirements for the emittance preservation along the LHC Injectors Complex is discussed.

INTRODUCTION

The PSB is the first circular accelerator in the LHC injector chain, consisting of 4 rings that have a common injection and extraction beamline. The PSB is where the brightness, defined as the ratio between the beam intensity and the transverse beam emittance, i.e. $2\,N_b/(\epsilon_x+\epsilon_y)$, of the LHC beams is determined and is dominated by space charge effects at injection [1].

The PSB presently undergoes major changes as part of the LIU project, aiming to increase the beam brightness of the LHC beams by a factor of 2. In order to achieve this goal, tight budgets on losses and emittance degradation along the injector chain have been defined [2].

During the entire LHC Run 2, a systematic horizontal emittance discrepancy of the order of 50% was observed for the operational LHC beams between the PSB extraction and the PS injection [3,4]. The operationally used transfer line optics results in a significant mismatch of the horizontal dispersion at the PS injection, which can explain only part of the observed discrepancy (i.e. 20 %). Various studies were dedicated in past years to identify the possible sources leading to this effect [5–7].

In this paper, the impact of systematic errors on the transverse emittance measurement in the PSB is analysed. In 2018, a systematic transverse emittance versus beam intensity measurement campaign was performed [8,9]. The measurements were carried out in all 4 PSB rings using the operational wire scanners (WS) at extraction energy (1.4 GeV). The beam was then extracted and sent either to the Booster Transfer Measurement (BTM) line or to the Booster Transfer to PS (BTP) line and eventually to the PS. The transverse emittance was then measured with either the Secondary Emission Monitor (SEM) grid system located in the BTM line or with the PS wire scanners 15 ms after injection, respectively. The longitudinal beam profile was also measured for each case. The measurements were performed on the operational BCMS (Batch Compression, Merging and Splitting) beam type, for an intensity range of 60-100×10^{10} protons per bunch. The nominal intensity for the BCMS beam in 2018 was 75×10^{10} ppb.

EMITTANCE MEASUREMENTS

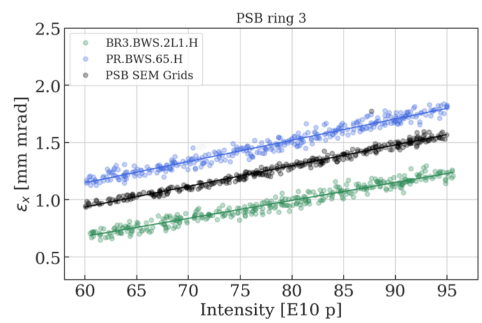

Figure 1: Horizontal emittance versus intensity, as measured with the PSB WS (green), the PS WS (blue) and the SEM grids in the BTM line (black).

Assuming a measured transverse beam profile and Gaussian beam distributions in all 3 planes, the transverse emittance of the beam can be defined as:

$$\epsilon_{x,y} = \frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2(\delta p/p)^2}{\beta_{x,y}}, \qquad (1)$$

where: $\sigma_{x,y}$ is one standard deviation from a Gaussian fit over the horizontal (x) and vertical (y) beam profiles; $\beta_{x,y}$ are the horizontal and vertical beta functions and $D_{x,y}$ the dispersion at the location where the profile is measured; $\delta p/p$ is the momentum spread of the beam. The emittance computation using the SEM grid profile measurements is based on the 3 grid method [10]. In all cases the momentum profiles are computed from the multiple acquisitions of the bunch length using a tomoscope application [11,12]. Table 1 summarises the optics parameters at the location of the wire scanners in the PSB and the PS, based on the perfect optics models of the two accelerators.

Figure 1 shows the horizontal emittance measurement as a function of the beam intensity for ring 3, using the beam size measured with the PSB WS (green), the PS WS

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(blue) and the SEM grid in the BTM line (black). A large emittance difference is observed between the PSB and PS WS measurements, consistent with the 50% discrepancy observed in operation. However, the measurements using the SEM grid lie between the PSB and PS WS curves. Similar observations were also reported in 2017 [13], for the nominal BCMS beam. All the 4 PSB rings show a similar behavior. The linear dependence observed in Figure 1 comes from the fact that the PSB runs at constant brightness, as a result of the large space charge tune spread at injection ($\delta Q \approx 0.5$) [1].

IMPACT OF SYSTEMATIC ERRORS

For the emittance calculations of Figure 1 the values of the optics at the location of the WS were taken from the optics models of both machines. Figure 2 shows an analytical parameterisation (based on Eq. (1)) of the emittance error, with a relative error up to ±10% in both the beta function and the dispersive contribution, for the case of the PSB (left) and the PS (right). These plots reveal the strong impact of an error in the optics functions used for the emittance computation. Consequently, an optics measurements campaign took place in both the PSB and the PS in 2018, presented in [14, 15].

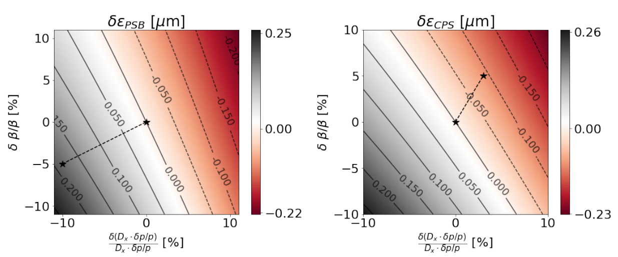

Figure 2: Analytical parameterization of the error in the emittance computation with the relative β and dispersive part error, for the PSB (left) and the PS (right). The two stars indicate the model ($\delta\epsilon = 0$) and the case of the measured optics functions.

Optics Measurements

Figure 3 shows the PSB horizontal beta function measurement at the Beam Position Monitor (BPM) around the machine. The dispersion can be precisely measured at the location of the WS by changing the radial steering and measuring the mean radial position as a function of the RF frequency. The measured dispersion is 7% smaller than the model one in the case of the PSB and 5% larger in the case of the PS. On the other hand, even though the PSB is equipped with a turn-by-turn BPM system (16 BPM per ring, one per period), the optics measurements are dominated by large uncertainties due to the 90^o phase advance between the BPM and the BPM calibration errors [14]. The PSB WS are located in the middle between 2 consecutive BPMs, as indicated in Figure 3 and the estimation of the relative beta error at this location is of the order of $\delta\beta/\beta$=(-10±20)%. For the case of the PS, the beta function is precisely measured and is very close to the model one, with a relative beta error of less than 5% [15]. The measured optics functions at the location of the WS in both machines are summarised in Table 1.

Table 1: Optics Functions at the Location of the Wire Scanners in the PSB and the PS

WS	PSB *BRi.BWS.2L1.H*	PS *PR.BWS.65.H*
β_x **model**	5.7 m	22.3 m
β_x **meas.**	5.1 ± 1.0 m	22.9 ± 1.1 m
D_x **model**	1.47 m	3.02 m
D_x **meas.**	1.35 ± 0.02 m	3.17 ± 0.05 m

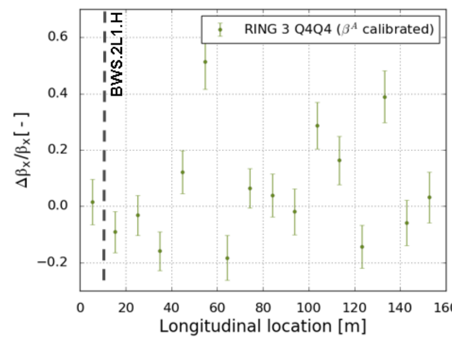

Figure 3: PSB horizontal beta beating measurement around the machine.

Using the measured optics at the location of the wire scanners in both PSB and PS the horizontal emittance versus intensity curves were recomputed and the results are summarised in Figure 4. The errorbars include dispersion and beta measurement errors.

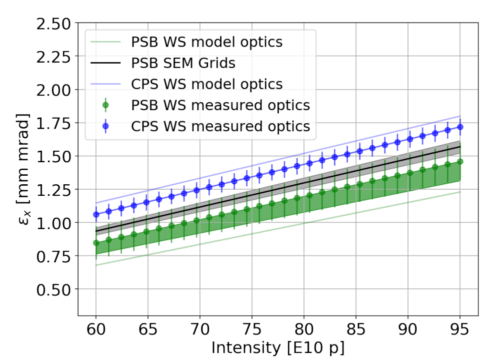

Figure 4: Horizontal emittance as a function of intensity as measured by the PSB WS (green), the PS WS (blue) and the BTM SEM Grids (black) including the systematic errors in the dispersion and beta functions.

Based on the above assumptions, the upper limit of the PSB WS curve would be compatible with the PSB SEM grids curve, giving a strong indication that the large emittance blow up observed in operation is dominated by systematic errors. Another very interesting observation is the fact

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that the difference between the PS curve using the measured optics functions and the SEM grids curve, would match the expected emittance blow up due to the dispersion mismatch in the transfer line between the PSB and the PS [16]. However, the large uncertainty in the beta function measurements does not allow for a solid conclusion. Further studies are currently in progress for improving the beta function measurements in the PSB.

Full Deconvolution of the Measured Beam Profile

Due to the presence of dispersion at the location of the WS and the SEM grids, the horizontal beam profile is a convolution of the betatronic and dispersive contributions. In the previous analysis, the Gaussian beam profile assumption was used. In the case of the PSB, however, the longitudinal distribution follows a non-Gaussian shape, as shown in Figure 5 (orange). An experiment was therefore setup to study the error introduced in the emittance calculation by the assumption of Gaussian profiles in all planes.

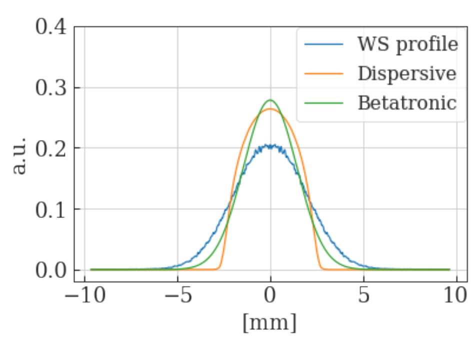

Figure 5: Measured beam profile from the PSB WS in comparison to the dispersive and betatronic profiles computed with the full deconvolution algorithm.

The PSB is equipped with a double harmonic RF system. In nominal conditions, for BCMS beams, the voltage of the main harmonic (h=1) is V_{rf}=8 kV while the voltage in the second harmonic (h=2) is very small, producing a longitudinal emittance of $\epsilon_l = 4\pi\sigma_\tau\sigma_{\Delta E}$=0.9 eVs and a momentum spread of 0.9×10^{-3}. For the purpose of this experiment, the voltage function in the second harmonic RF system was modified in order to produce momentum spread values up to 1.3×10^{-3}. The same was done for 3 different beam intensities, i.e. 55E10, 75E10 and 100E10 ppb. For each point, the transverse profiles were recorded either with the wire scanner or with the BTM SEM Grids and the longitudinal profiles with the wall current monitor. A tomoscope analysis was then applied in order to reconstruct the momentum distributions. The horizontal emittance was finally computed using the standard Gaussian subtraction (Eq. (1)) and the full deconvolution method (see [11,12]). In the first case, the rms δp/p computed from a binomial fit is used. Figure 6 shows the relative difference between the two methods with respect to the relative momentum spread. The 3 curves correspond to the 3 different intensities. It becomes clear that the two methods diverge when the contribution of the dispersive part

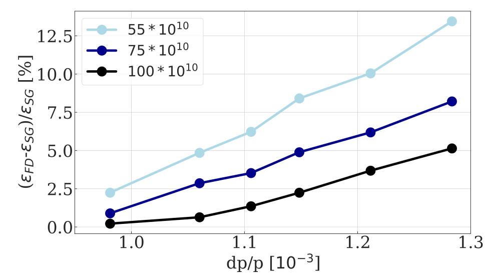

Figure 6: Relative difference between the standard Gaussian subtraction in quadrature and the full deconvolution methods for the emittance computation, versus the relative momentum spread.

of the profile becomes larger, i.e. for larger $\delta p/p$ and smaller betatronic profiles, i.e. for smaller intensities. In a similar manner, the impact of the distribution shape on the emittance computation was also studied in simulations for the PS [17], arriving to similar conclusions. This error contribution is small for the current BCMS beams (δp/p=0.9×10^{-3}), however, it is expected to become more important for the LIU beams with larger longitudinal emittance. Further studies are currently in progress in simulations to help identify the optimal emittance computation algorithm for minimizing the impact of this source of systematic error.

SUMMARY AND OUTLOOK

An important horizontal emittance discrepancy between the PSB extraction and the PS injection has been observed in operation for the LHC beams in the entire LHC run 2. Part of it can be explained by the dispersion mismatch in the transfer line, however, a large part still remains not understood. In this paper, the impact of systematic errors on the horizontal emittance measurement in the PSB was discussed. It was shown that by using the measured beta and dispersion functions at the location of the wire scanners in both the PS and PSB, the difference between the emittance measurements is reduced. However, the large uncertainty in the beta function measurement at the location of the PSB wire scanners does not allow to reach solid conclusions. The systematic error coming from the emittance computation algorithm used is also discussed. A comparison between the standard Gaussian subtraction and the full deconvolution methods showed a clear increase in the divergence between the two methods when the dispersive contribution to the measured transverse profile becomes larger. This source of error is expected to become more important for the LIU beams, where the longitudinal emittance will also be larger. Further simulation studies are in progress for identifying the optimal emittance computation algorithm.

ACKNOWLEDGEMENT

The authors would like to thank the PSB and PS operation teams for their assistance during the data taking. The authors would also like to thank F. Roncarolo and A. Guerrero Ollacarizqueta for their support whenever needed.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS087

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