COMPARISON OF DIFFERENT TRANSVERSE EMITTANCE MEASUREMENT TECHNIQUES IN THE PROTON SYNCHROTRON BOOSTER

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Abstract

The measurement of the transverse emittance in an accelerator is a crucial parameter to evaluate the performance of the machine and understand beam dynamics processes. In recent years, controlling and understanding the emittance became particularly relevant in the Proton Synchrotron Booster (PSB) at CERN as part of the LHC Injectors Upgrade (LIU). The LIU project is a necessary step to achieve the goals of the High-Luminosity LHC project. In this framework, an accurate and reliable emittance measurement of high brightness beams is mandatory to study the brightness reach of the LHC injectors. In the PSB there are two main instruments available for emittance measurements: wire scanners and secondary emission monitor grids. In this paper emittance measurements performed during the 2017 physics run with these two systems are compared, taking into account various systematic error sources.

INTRODUCTION

The performance of the current LHC injector chain, although allowing to double the design instantaneous luminosity of the LHC in 2017, is not sufficient to meet the requirements for the High Luminosity LHC (HL-LHC) [1]. In order to achieve the desired goal, the LHC Injector Upgrade (LIU) project aims at doubling the brightness of the beams provided to the LHC [2]. As part of the upgrade, the CERN PS Booster (PSB) will implement a new H^- charge-exchange injection system to be able to receive the H^- beam at a kinetic energy of 160 MeV from Linac4 [3]. The increase of energy at PSB injection with respect to the 50 MeV protons from Linac2 should provide more than a factor 2 in space charge tune spread reduction, $(\beta\gamma^2)^{160\,\text{MeV}}/(\beta\gamma^2)^{50\,\text{MeV}}$, which is the driving effect limiting the PSB brightness reach.

Since the PSB is the first accelerator in the LHC proton injector chain, it defines the minimum normalized transverse emittance of the LHC beams. In order to be able to match the HL-LHC target, the transverse emittance blow-up budget is limited to 5% from PSB extraction to the CERN Proton Synchroton (PS) extraction. These boundaries automatically constrain the precision and accuracy of the transverse emittance measurements.

Previous measurements in the PS machine showed the challenges of achieving the targeted performance [4]. Recent analysis of the emittance evolution along the PSB cycle [5] confirmed the difficulties of accurately measuring the transverse emittance, particularly in the horizontal plane, where the transverse betatronic beam profile is convoluted with the dispersive contribution.

In recent years a larger than expected transverse emittance blow-up has been measured at the PS injection [6]. Some blow-up is, in fact, expected due to a known dispersion mismatch between the two machines, which is unavoidable with the current optics configuration. In this context, a precise absolute measurement of the transverse emittance at the PSB extraction is also crucial to understand the starting point for the undesired emittance growth currently observed at PS injection.

The PSB is an accelerator composed of 4 superposed rings which accelerate protons injected at 50 MeV from Linac2 up to 1.4 GeV before extraction. Each PSB ring is equipped with two wire scanners (WS) to measure beam profiles in both planes independently. The machine is also equipped with 3 secondary emission monitor (SEM) grids in the measurement extraction line (BT-BTM) and each device can measure beam profiles in both horizontal and vertical planes. Having different instruments or techniques monitoring the same quantity allows for comparison with the ultimate goal to obtain unbiased results. At the same time, it allows to validate each system and identify issues which would otherwise remain unnoticed with a single instrument.

MEASUREMENTS SETUP AND TECHNIQUES

Wire Scanners

Wire scanners are the reference equipment to monitor the evolution of the transverse emittances in the LHC injectors. The normalised emittance is generally calculated according to Eq. (1)

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{\text{rel}} \gamma_{\text{rel}}, \qquad (1)$$

where $\sigma_{x,y}$ is the beam size, $\beta_{x,y}$ is the beta function, $D_{x,y}$ is the dispersion function, δ is the momentum spread, β_{rel} and γ_{rel} are the relativistic factors.

The optics functions $\beta_{x,y}$ were obtained using the simulation tool MAD-X [7], while the horizontal dispersion was measured by varying the revolution frequency at PSB extraction which, in turn, yields a variation of the momentum offset and consequently a displacement of the center of the beam correlated with the dispersion. As an example, the

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comparison between the simulated and measured horizontal dispersion in PSB ring 1 and extraction line to the dump is shown in Fig. 1. In general, the horizontal dispersion was found to be about 10% lower in absolute value than predicted at the WS location, while a good agreement with the simulation was found at the SEM grids.
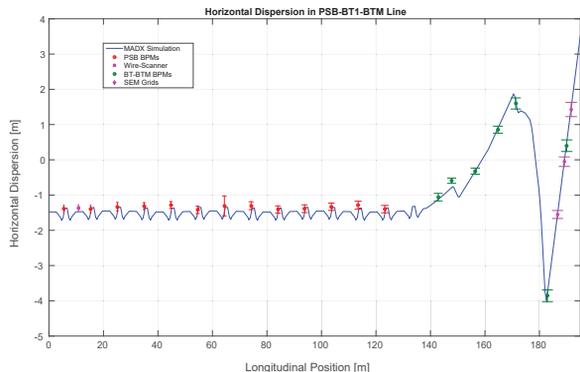
Figure 1: Data and MAD-X simulation (blue) comparison of the horizontal dispersion measured at the beam position monitors (red) and WS (magenta) location in PSB ring 1 and beam position monitors (green) and SEM grids (magenta) in the extraction line to the dump.

When removing the dispersive contribution from the total profile, the root mean square (RMS) distribution of the momentum spread is typically used. The underlying assumption is that both the betatronic and the momentum spread profiles follow a Gaussian distribution. The momentum spread measured at PSB extraction instead exhibits a parabolic distribution. Thus, for the analysis reported in this paper the measured transverse beam profile is assumed to be a convolution of the dispersive contribution and the betatronic one and, as such, the betatronic profile is obtained resolving the convolution equation [4]. It has also been assumed that the betratronic profile has a Gaussian distribution. This hypothesis improves the algorithm stability and its validity will be discussed later in the paper.

SEM Grids

The 4 beamlets from the PSB rings are vertically recombined with two sets of recombination kickers and septa in the so called Booster Transfer (BT) line. At the end of the BT line a switching dipole allow to send the beam to either the PS or into a measurement line ending with a dump. The latter is referred to Booster Transfer Measurement (BTM) line. This line allows to perform measurements of the transverse emittance and Twiss functions with the 3 pairs of SEM grids [8]. For a given plane, the optics model is designed such that the beta function is symmetric and minimised with respect to the central grid. Since the parabolic beta function is minimal at the second SEM grid, the wire separation has been chosen to be 0.5 mm in the middle grid and 1.0 mm in the external grids. In the PSB the 3 SEM grids are only separated by a drift space, which is nominally long about

2.5 m and has been measured with a precision of the order of cm. Such a configuration greatly simplifies the construction of the response matrix. In order to not rely on simulated parameters also the horizontal and vertical dispersion were measured at the location of the grids. As one can see in Fig. 1, the dispersion varies depending on the grid position and, in some cases, is comparable to the one measured in the PSB rings. For this reason also the betatronic profile at the SEM grids is obtained with the full deconvolution of the dispersive distribution.

Additionally, in 2017 the possibility to determine the transverse emittance via quadrupole scan was explored [8]. For the measurement setup, the second grid with the smallest wire spacing was selected in combination with the focusing quadrupole BTM.QNO20, located at about 6.9 m upstream the grid. In order to resolve the minimum of the parabola, a 'dispersion-free' optics at the grid was proposed, see Fig. 2. The optics is designed to have minimal dispersion variations for the range of the scanned quadrupole strengths. While additional investigation is still needed to validate and employ the technique in standard operation, the first important result was obtained after analysing the profile at the grids. The measured beam profile was found to be distributed according to a Gaussian in absence of dispersion. This confirmed that the assumption done for the betatronic profile to follow a Gaussian distribution is satisfied.
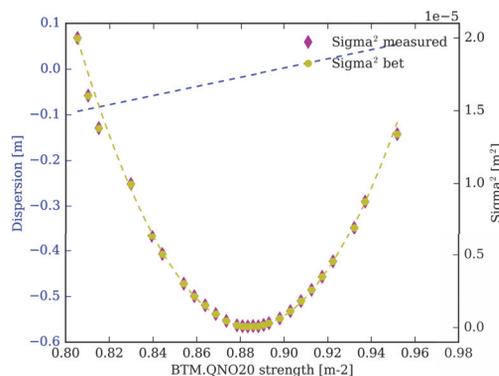
Figure 2: The 1-σ beam size squared, before and after removal of the RMS momentum spread using Eq. (1), and dispersion as a function of the strength of BTM.QNO20 used for the quadrupole scan with the 'dispersion-free' optics.

Results

Comparative transverse emittance measurements with the WS and the SEM grids were carried in 2017 using the Batch Compression Merging and Splitting (BCMS) beam production scheme, partially employed during the LHC physics run to allow for higher brightness than the conventional 25 ns scheme [6].

Both measurements were performed synchronously on the same beam at PSB extraction (WS) and on the BTM

line (SEM). This allowed to remove systematic differences which may have come from analysing different beam cycles.

Due to calibration issues the WS in the vertical plane in ring 1 and ring 3 were operated at a speed of 10 m/s, while the remaining WS were operated at the maximum speed of 15 m/s.

In Fig. 3 the relative difference between the WS and the SEM grids measurements is shown. A large discrepancy in the measurements in ring 1 vertical plane is observed, likely related to a calibration issues with the WS. Excluding this data from the comparison, the SEM grids measure an emittance which is 5%-20% higher than the one extracted with the WS profiles. The analysis of the residuals showed that generally the SEM grids measurements have a smaller spread than the WS ones. The resolution of the SEM grids was probed by reducing the beam intensity and hence the beam size at the wires, and the emittance was found to follow the expected linear scaling. A detailed simulation of the SEM grid performance as a function of the wire spacing and beam intensity will be performed to validate the observation in 2017.

The WS flying through the beam causes a blow-up of the transverse profile due to Coulomb scattering of the protons in the bunch with the wire. The effect of the blow-up is currently being investigated and has not been explicitly removed in this analysis [5]. The blow-up at the SEM grid due to the WS was measured to be of the order of few % and it would not be enough to absorb the observed discrepancy between the two instruments.
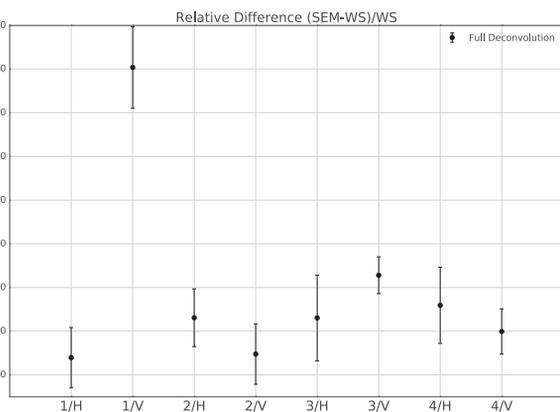
Figure 3: Relative emittance difference between the measurement performed with the 3 SEM grids and the wire scanner. In both measurements the dispersion contribution was removed with the deconvolution technique explained in [4].

In the described analysis the only parameter obtained from simulation is the beta function at WS location at the extraction tune. At the beginning of 2017 the PSB rings have been equipped with turn-by-turn beam position monitors [9]. The system has been commissioned in 2017 and the plan

is to measure the beta-beating at PSB extraction in 2018 to check if it could account for the observed discrepancies between instruments.

Following this analysis, both WS in ring 1 and ring 3 vertical plane have also been replaced at the beginning of 2018 with newly calibrated ones.

Conclusions

In this paper, we presented complementary transverse emittance measurements in the PSB at the extraction kinetic energy of 1.4 GeV using different instrumentation. A systematic difference in the measurement of the transverse emittance between the WS and the SEM grid was observed for the BCMS proton beam production scheme, operationally used in LHC during 2017. In order to conclude on the absolute betatronic transverse emittance further analysis is needed. A measurement of the beta-beating at the WS location would allow determining experimentally all optics input and improve the understanding of the differences. Thanks to the redundant emittance measurements, calibration issues with the WS in ring 1 vertical plane were observed and the equipment replaced at the beginning of 2018. The first attempt to measure the emittance employing the quadrupole scan technique was made. For this technique, a dedicated optics model was developed that needs additional investigation before employing it in operation. Its viability will be pursued further in 2018.

ACKNOWLEDGMENTS

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