HORIZONTAL DISPERSION STUDIES FOR THE CERN PROTON SYNCHROTRON BOOSTER RINGS

V. Raginel, B. Mikulec, S. Gilardoni, CERN, Geneva, Switzerland

Abstract

In order to confirm the value of horizontal dispersion of the CERN Proton Synchrotron Booster (PSB) given by the MADX model, the horizontal dispersion has been measured using pick-ups and wire scanners on its four rings. The dispersion value of the PSB rings is of interest for example as input for the emittance measurements critical for high-brightness beam production for the LHC, for future optics studies related to the planned upgrades of the PSB or for optics studies of the ejection lines. In this study, the dispersion measurement protocol and the analysis of the measurements are presented. The measurement results point out differences with respect to the MADX model and also differences between the four rings. It was then investigated using horizontal orbit measurement and MADX matching routines whether misalignments of quadrupole magnets could explain these differences.

INTRODUCTION

The knowledge of the dispersion of the Proton Synchrotron Booster (PSB) rings is of interest for cross check the optics of the ring currently in use, but also as input for the emittance measurements [1] or for the optics matching studies of the injection/ejection lines. While the dispersion in the PSB is estimated by a MADX model [2], measurements of dispersion are necessary to validate the simulated optics. The horizontal dispersion $D_x(s)$ can be defined by:

$$\Delta x(s) = D_x(s) \cdot \delta$$

where $\Delta x(s)$ is the horizontal beam centroid displacement at the location s and $\delta=\Delta p/p_0$ is the relative momentum offset with respect to the nominal momemtum p_0. The dispersion can be measured by changing the beam momentum via the RF system, observing the beam displacement at the location of the beam position monitors and the variation of the revolution frequency. The momentum deviation is evaluated via the momentum compaction factor and the measured frequency change. The measurements were done for all four rings of the PSB. The dispersion was obtained off-line using a fitting routine on the beam position monitors data and then compared to the MADX model.

DISPERSION MEASUREMENTS

The dispersion was measured using a LHC 50 ns beam (the luminosity production beam for the LHC 2012 run) for each ring using the programmable RF radial position function which converts a given change in the average orbit into energy offset. The radial position function was modified 760 ms after the start of the cycle, just before the extraction flat top of the magnetic cycle when the beam momentum is 2126 MeV/c. The horizontal beam displacement and the revolution frequency were acquired for various values of the radial position function averaging over three measurements. The horizontal beam displacement was observed by the sixteen pick-ups of each ring (BRi.UES1L3, BRi.UES2L3 ..., and BRi.UES16L3, with i=1, 2, 3, 4 indicating the fours PSB rings), one pick-up per section, and by one wire scanner in the section 2 of each ring (BRi.BWS.2L1). The pick-ups of the PSB rings are installed in-between the first focusing quadrupole (QF) and the defocussing quadrupole (QD) with the basic optics cell of the PSB being bending1-QF1-QD-QF2-bending2. The readout chain per section of the pick-ups is the same for each ring (multiplexing) [3].

A too large horizontal beam displacement can cause beam losses when the aperture limit is reached. The maximum variations of the radial position function with no beam losses were determined for both positive and negative displacement. The measurements were done between these maximum variations.

DISPERSION ANALYSIS AND RESULTS

Determination of the Dispersion in Each Ring

The measurements yield the displacement of the center of the beam and the corresponding revolution frequency. The relative momentum deviation was derived from the relative variation of the revolution frequency thanks to the following relation:

$$\Delta f / f_0 = -\eta \cdot \delta$$

where $\eta = \eta_0 + \eta_1 \delta + O(\delta^2)$ is the phase slip factor [4]. The frequency f_0 corresponds to the naturally centered orbit by introducing no offset in the radial loop function. A first assumption is to simplify the phase slip factor to the first order. The analysis was done using the relation

$$\Delta f / f_0 = -\eta_0 \cdot \delta$$

where $\eta_0 = \alpha_0 - 1/\gamma^2$ with α_0 being the first order momentum compaction factor, which is equal to 0.0609 in the PSB, and γ being the relativistic gamma of the proton beam. Δx vs. δ is then plotted for each pick-up and the wire scanner, examples of a plot of Δx vs. δ is shown in Figure 1 (black dashed line). The data fits show that the data is not linear, but rather parabolic.

ISBN 978-3-95450-138-0

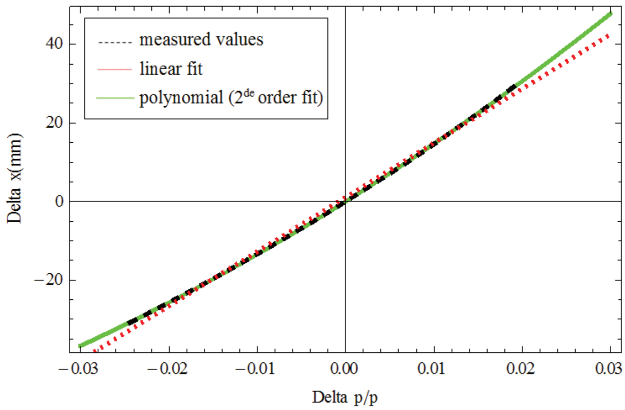

Figure 1: Plots of Δx vs. δ resulting from measurements done on the pick-up BR1.UES5L3 using the simplified relation $\Delta f/f_0 = -\eta_0 \cdot \delta$.

A second analysis was subsequently done using the relation

$$\Delta f / f_0 = -(\eta_0 + \eta_1 \cdot \delta) \cdot \delta$$

where $\eta_1 = \alpha_0 \cdot \alpha_1 + 3\beta^2 / 2\gamma^2 - \eta_0 / \gamma^2$ [5]

with α_0 being the first order momentum compaction factor and α_1 being the second order momentum compaction factor. The second order momentum compaction factor was determined for the PSB in the same way already used before in the PS [6]. The second order momentum compaction factor α_1 is related to the total momentum compaction factor α_p given by the MADX model of the PSB:

$$\alpha_p = \alpha_0 (1 + 2\alpha_1 \delta) + O(\delta^2) \; [4]$$

The total momentum compaction factor α_p was simulated for nine momentum offsets Δp = ±40, ±30, ±20, ±10 and 0 MeV. α_1 was then derived from the slope of α_p vs. δ, and yields α_1 = 2.237. The resulting horizontal beam displacement as a function of the relative momentum spread becomes then a linear function. The relative position error of the pick-ups is considered to be within ±0.1 mm, except for the pick-ups 2L3 and 10L3 (±0.2 mm and ±0.3 mm, correspondingly) [7]. The calibration of the wire scanners indicates that the response of the wire scanners is linear in the range ±10 cm and that the relative horizontal position error is negligible. The data of the pick-ups BR2.UES6L3 and BR2.UES10L3 show some incoherency with the others pick-ups probably due to malfunctioning of the system and thus are excluded from the analysis. The slope of the linear fit gives the dispersion at each measurement point in the four rings. A comparison of the measured horizontal dispersion of all four rings and the horizontal dispersion D_x predicted by the PSB MADX model is shown in Figure 2. One can see in Figure 3 that the maximal relative differences of D_x predicted by the PSB MADX model and obtained by measurements on the 4 rings is ~10%. The dispersion values of MADX agree rather well with the measured values; however the dispersion of the MADX model shows an offset of ~0.05 m compared to the dispersion measured in the 4 rings, which is not well understood yet. The measurements show that dispersion is different from ring to ring, in the next section it is investigated whether misalignments of the defocusing quadrupoles explain these differences.

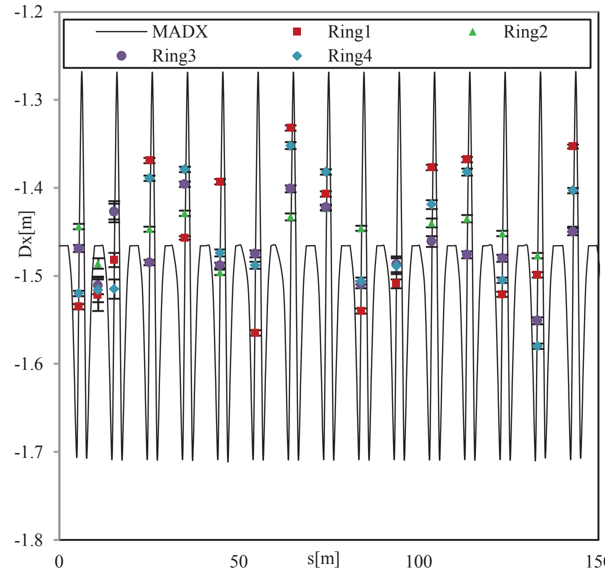

Figure 2: MADX simulation of the horizontal dispersion along the PSB ring (solid line) with the measurement points for the horizontal dispersion D_x for the 4 rings.

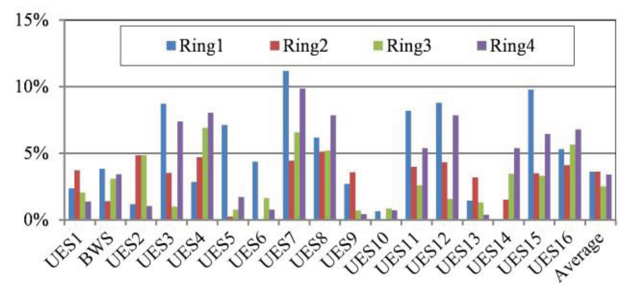

Figure 3: Relative differences of D_x given by the MADX model and obtained by measurements for the 4 rings. The pick-ups UES6 and UES10 of Ring2 are excluded from the analysis.

Analysis of the Differences Between the PSB Rings

It is investigated if the differences in dispersion between the four rings could be explained by the horizontal misalignments of the defocusing quadrupoles (QD). It has to be noted that a tilt of each QD affects differently the four superposed rings of the PSB because the alignment of the rings for the tilt is done by rotating the magnet stack around the centre of ring 3, which is at the same vertical level than the injection/extraction line. The method used was to estimate the horizontal misalignments of the QDs from closed orbit measurements for each of the four rings and then to compute the horizontal dispersion ring by ring inserting the estimated misalignments into the MADX model.

As the closed orbits in the PSB are dominated by misalignment effects [8], the horizontal misalignments of the defocusing quadrupoles can be estimated as follows. First the horizontal closed orbits were measured 760 ms after the start of the cycle for all the four rings averaging over three measurements, including the transversal misalignments of the pick-ups. Second in the MADX model, virtual horizontal kickers were inserted in the centre of each QD to represent the misalignments of the QDs. Their strength was then determined by reproducing the closed orbit via the MADX model. The kicks were then translated into misalignments using the relation $\Delta x_{QD} = \theta/(L\cdot k)$ with Δx_{QD} being the horizontal misalignment of the defocusing quadrupole, θ being the kick found by matching, L being the magnetic length of the quadrupole and k being the normalized gradient of the quadrupole. The estimation of the horizontal misalignment of the QDs was done independently ring by ring. Finally the estimated horizontal misalignments of the QDs were introduced into the original MADX model and the closed orbit and dispersion were computed. The dispersion function at the pick-ups is not strongly dependant on the number of misaligned QDs, when using two or more misaligned QDs.

From Figure 4, one can note that the offset between the measured dispersion and the one given by the MADX model is ~0.06 m. The misalignments of the QDs in the MADX model induce an oscillation of the dispersion around its average value. These oscillations agree rather well with the oscillations observed in the measured dispersion as shown in Figure 4 for rings 1, 3 and 4. For ring 2 it is difficult to conclude, as the dispersion measurement does not have a clear dispersion pattern due to the exclusion from the analysis of the pick-ups UES6 and UES10. It has to be noted that the absolute error of the pick-up orbit measurement is estimated to be ~1 mm [9], which leads to uncertainties on the estimated misalignments of the QDs and subsequently on the estimated dispersion with these misalignments.

However there are good indications that the misalignments of the QDs in the PSB explain the oscillations of the dispersion around its average value and thus explain partially the differences of the measured horizontal dispersion between the four rings.

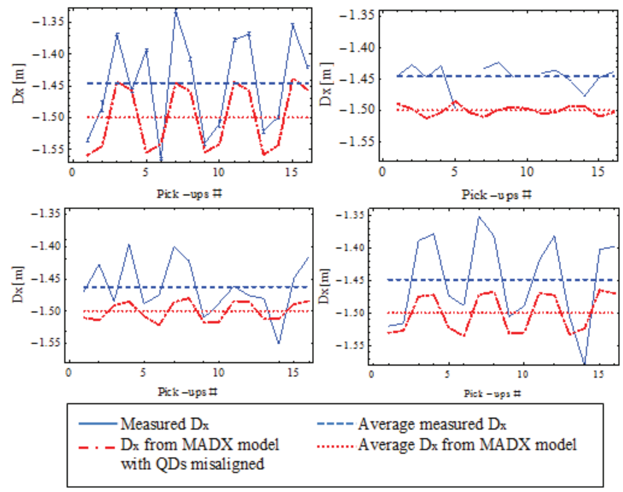

Figure 4: Comparison of the measured horizontal dispersion at the 16 pick-ups with the dispersions given by the PSB MADX model with misalignments of the QDs for ring 1 (top left), ring 2 (top right), ring 3 (bottom left) and ring 4 (bottom right).

CONCLUSION

The horizontal dispersion was measured using 16 ring pick-ups (1 per section) and a wire scanner (1 per ring) for the 4 rings of the PSB. The measured horizontal dispersion is consistent with the values of MADX within maximum 10% relative error and amounts to -1.45 m in average at the pick-ups. However slight differences between the four rings were observed. Using orbit measurements to estimate the misalignments of the QDs in each of the four rings it was shown that the difference in horizontal dispersion between the four rings could be partially explained by misalignments of the QDs. During the long shutdown 2013-2014 the PSB rings have been realigned; according to this study it can be expected to obtain a more uniform horizontal dispersion between the four rings after the 2014 restart.

REFERENCES

[1] P. Forck, Lecture Notes on Beam Instrumentation and Diagnostics, page 40, JUAS 2011.
[2] http://project-ps-optics.web.cern.ch/project-PS-optics/cps/Psb/2013
[3] D. Korchagin, M. Ludwig, L. Soby, BI Front end software functional specifications for the PSB Orbit measurement system [BPBNO], EDMS 691997, 2007.
[4] S.Y. Lee, Accelerator Physics, page 219, 1999.
[5] J.P. Shan, S.G. Peggs, S.A. Bogacz, Analytical evaluation of the second order momentum compaction factor and comparison with MAD results, Fermilab, 1993.
[6] S. Aumon, High Intensity Beam Issues in the CERN Proton Synchrotron, CERN-THESIS-2012-261.
[7] M. Chanel, B. Mikulec, G. Rumolo, R. Tomás, PS Booster Orbit Correction, CERN-AB-2008-034.
[8] C. Carli, Closed Orbit Estimates according to known misalignments in the PS Booster, PS/CA/Note 97-21.
[9] L. Soby, *private communications.*

ISBN 978-3-95450-138-0