ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF088

CERN PS BOOSTER UPGRADE AND LHC BEAMS EMITTANCE

E. Benedetto, J. L. Abelleira, C. Bracco, B. Mikulec, G. Rumolo, CERN, Geneva, Switzerland,
V. Forte, CERN, Geneva, Switzerland, and Université Blaise Pascal, Clermont-Ferrand, France

Abstract

By increasing the CERN PS Booster injection energy from 50 MeV to 160 MeV, the LHC Injector Upgrade Project aims at producing twice brighter beams for the LHC. Previous measurements showed a linear dependence of the transverse emittance with the beam intensity and space-charge simulations confirmed the linear scaling. This paper is discussing in detail the dependence on the longitudinal emittance and on the choice of the working point, with a special attention to the H^- injection process and to the beam dynamics in the first 5 ms, during the fall of the injection chicane bump.

INTRODUCTION

As part of the LHC Injectors Upgrade Project (LIU), the CERN PS Booster (PSB) will undergo an upgrade program [1], which includes the increase of injection energy from 50 MeV to 160 MeV and the implementation of an H^- charge-exchange injection from the new Linac4. Compared to the other rings with H^- injection and characterized by similar space-charge tune spreads at low energy ($\Delta Q \sim 0.5$ [2]), the peculiarity of the PSB is the required small transverse emittance. This needs to be produced and preserved in order to provide high brightness beams to the LHC. Being the first circular accelerator in the LHC proton injector chain, the PSB defines the minimum normalized transverse emittance.

The paper will review the measurements done in 2012 to characterize the operational LHC type beams in the PSB [3], which show a linear dependence of the transverse emittance with the beam intensity. The increase of injection energy with LIU should give about a factor $(\beta\gamma^2)^{160\mathrm{MeV}}/(\beta\gamma^2)^{50\mathrm{MeV}} = 2.04$ reduction of the space-charge tune spread for the present beams. Assuming the same tune spread as of today, which is in our baseline [4], with Linac4 it will be possible to inject twice the intensity in a given emittance (or to reduce the emittance by the same amount), i.e. the brightness curve should scale down by a factor 2. Simulation results will be presented to confirm these estimates and to discuss the dependence on the working point and on the longitudinal emittance of the minimum emittance achievable for a given intensity. Finally, the H^- injection scheme to produce in a controlled way 1-1.5 μm emittances will also be discussed.

MEASUREMENTS

Figure 1 shows the linear dependence of the transverse emittance on the beam intensity, found with the measurements done in 2012 for the LHC-type operational beams [3]. Two sets of points are plotted in the figure, for the standard LHC beam (LHC25ns) which has a required longitudinal emittance of 1.20 eVs (matched area at extraction), and for the so called BCMS LHC beam [5], which undergoes a special RF gymnastics in the downstream machine, the PS, and needs to be provided to the PS with a longitudinal emittance of maximum 0.9 eVs.

Different beam intensities have been produced by increasing the number of injected turns from 1 to 4 and by optimizing the injection parameters including the tune to minimize the transverse emittances. The horizontal and vertical profiles have been measured at extraction in Ring 3, which featured the best performances as the result of a careful optimization.

Additional measurements [3] showed that, provided that the working point is optimized all along the cycle, the transverse normalized emittance is constant during acceleration (however measurements at injection are difficult to read due to scattering at the wires, inducing 10% blow-up during the measurement itself). This indicates that the final values of the transverse emittance are dominated by space-charge effects at injection energy and by the multi-turn injection process itself.

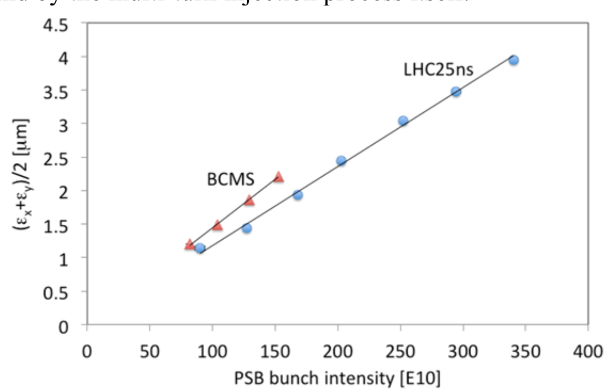

Figure 1: Emittance vs intensity curve for the LHC25ns beam (1.20 eVs) and the BCMS beam (0.86 eVs). Measurements of 2012 [3].

MINIMUM EMITTANCE SIMULATIONS

Simulations with PTC-Orbit [6] have been done to confirm the predictions of a factor 2 improvement in the brightness curve, assuming that the space-charge effects at injection energy in combination with machine errors are the cause of emittance blow-up.

The errors included in the model are the perturbations at the chicane magnets due to edge effect and Eddy currents [7]. Those provide the excitation of the half-integer and 20% vertical beta-beating, which is corrected down to a few % by special trims on two lattice quadrupoles. In addition to that, they induce the excitation

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF088

of the integer lines, which are not compensated. The model does not include any non-linear perturbations, except for the sextupolar components due to Eddy currents, which are negligible in strength.

In addition to those errors, the set of misalignments from 2012 survey data and the quadrupolar errors measured in the machine [8] are also optionally included, but represent a small contribution with respect to the chicane perturbations.

For the simulations to build the curve of the normalized emittance versus intensity, the multi-turn injection process is not included. A matched Gaussian beam with given initial values of intensity and transverse emittance is tracked over 7000 turns (~7 ms) and let evolve under space-charge forces during the fall of the chicane bump which is completed after 5 ms. The final emittance values are then used to build the curve of the average rms emittance $(\varepsilon_x+\varepsilon_y)/2$ versus intensity. This approach is justified by the results of Fig. 2, i.e. that the emittance reached at the end of the chicane bump is independent of the starting value. In the longitudinal plane, the distribution is uniform in phase and parabolic in energy spread with values of 632 ns (total length) and 336 keV (rms), which produces a longitudinal emittance after filamentation of 1.17 eVs. A second set of simulations assumes 1.48 eVs, which is achieved by an initial total bunch length of 600 ns and 403 keV rms energy spread [9].

The results presented in Fig. 3 are obtained for the baseline injection working point of (Q_x,Q_y) = (4.28,4.55) [10]. In blue and in red are the lines of Fig.1, scaled down by the factor 2 to account for the increase of the injection energy. The blue diamonds and the magenta squares show two different sets of data for the two different longitudinal emittances, respectively 1.17 eVs and 1.48 eVs. The simulated points lie as well on straight lines and it is confirmed that the increase in longitudinal emittance helps in improving the beam brightness. The simulated lines have a slope, which is 25% smaller than the analytical estimates.

A scan on the injection working point (Fig. 4) shows an even larger improvement if the horizontal tune is increased up to 4.43, which is around the present injection tune for the operational LHC beam (currently produced with 2-3 turn proton injection). Indeed, provided that the sextupolar or higher order resonance lines are not strongly excited (or they are adequately compensated with multipole correctors), as it is the case during present operation, the integer line excited by quadrupolar perturbation is the responsible for the beam blow-up. An increase of the working point therefore helps to accommodate a larger tune spread at injection.

Figure 5 shows the projections of the space-charge tune footprint on the horizontal and vertical axis. The initial tune spread for an intensity of 350e10 protons per bunch (ppb) and a starting emittance of 1 μm in both planes is shown in red (corresponding to the curves of Fig. 2). Since it extends largely below Q_x=4.0, the blow-up occurs mostly in the horizontal plane, and brings the tune footprint to the situation in blue. For comparison, in green the initial footprint for a simulation with a 1.7 μm initial emittance is plotted.

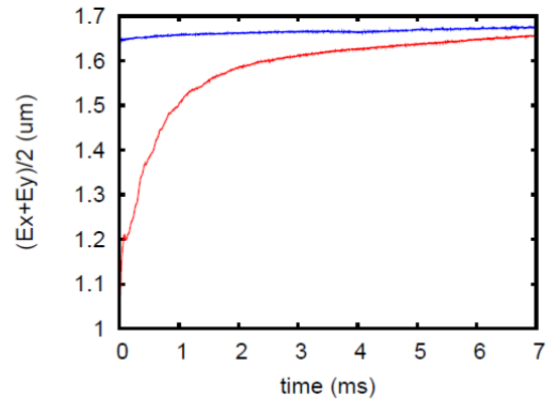

Figure 2: Simulated normalized average emittance evolution for a beam of 350e10 ppb and longitudinal emittance of 1.17 eVs, starting from 1.0 μm (red) or from 1.65 μm (blue).

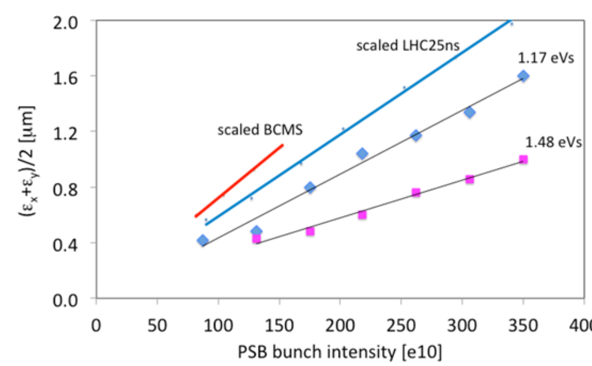

Figure 3: Average rms emittance versus intensity, assuming injection at 160 MeV from Linac4. Blue and Red lines correspond to the measurements results of Fig.1 scaled by a factor 2. Blue diamonds: simulations assuming 1.17 eVs longitudinal emittance. Magenta squares: simulations with 1.48 eVs.

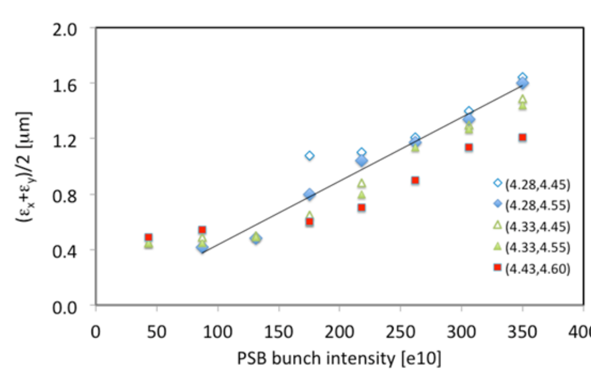

Figure 4: Simulated average rms emittance versus intensity, assuming 1.17 eVs longitudinal emittance and different injection working points.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF088

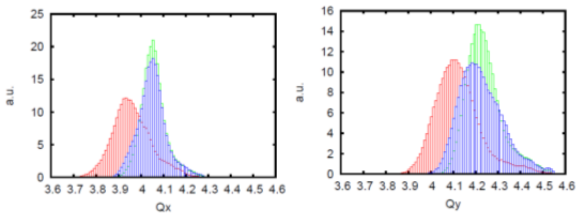

Figure 5: Simulated tune footprint, horizontal and vertical projections: Red: initial tune spread for a beam of 350e10 ppb and 1 µm emittances. Blue: final (after 7 ms) for the same beam. Green: initial footprint for 350e10 ppb and 1.7 µm. Longitudinal emittance is 1.17 eVs.

H- INJECTION PAINTING SIMULATIONS

In order to get 342e10 protons per bunch, which is the baseline value for the High Luminosity LHC [11], a multi-turn injection of 21 turns is needed assuming a Linac4 current at injection of 26 mA (and a fully matched 0.4 µm emittance beam).

Studies have been done to optimize the painting bump function [12] in order to achieve a normalized target transverse emittance of ~1.2 µm. This will allow to comfortably keep the final emittance below 1.6 µm, taking into account additional sources of blow-up such as possible mismatch or steering errors at injection and the blow-up due to space-charge effects in the low-energy part, i.e. during the fall of the chicane bump.

The simulations have been done with Orbit [13] and include space-charge effects and the Multipole Coulomb Scattering at the 200 µg/cm^2 thick Carbon injection foil. Figure 6 shows the horizontal painting bump function (a fixed offset of 3 mm is applied in the vertical plane) and the transverse emittance evolution during the H$^-$ multi-turn injection, for the baseline working point of (4.28, 4.55). Additional studies [12] have demonstrated that thanks to the painting flexibility it is possible to produce in a controlled way any emittance of 1-1.5um for the beams sitting on the brightness curve, for both working points considered in the emittance simulations, i.e. also for (Q_x,Q_y) = (4.43,4.60). Figure 7 shows that after the multi-turn injection process, the beam is Gaussian in both the horizontal and the vertical plane.

CONCLUSIONS

With space-charge simulations, which include the best available model of the machine (chicane magnet perturbations and a set of typical misalignment and quadrupolar errors), we have found the same linear dependence of the emittance versus intensity as in the measurements performed in the present machine. Simulations predict more than a factor 2 improvement of the beam brightness due to the increase of injection energy up to 160 MeV, as foreseen by the LIU. The choice of the injection working point may give additional margin as well as an increase of the longitudinal emittance. Injection painting simulations, including the scattering at the foil, demonstrated that it is possible to tailor any emittance sitting on the curve, for the two working points of interest.

Future work includes the simulations benchmarking with measurement after the present multi-turn proton injection in the present machine and end-to-end simulations of the emittance evolution during the first 7 ms, including the injection process and a realistic beam distribution from the Linac4.

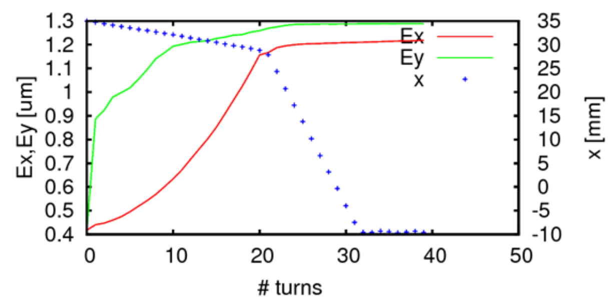

Figure 6: Simulated emittance evolution and horizontal bunch position during the 21-turn injection of 342e10 ppb and working point (Q_x,Q_y) = (4.28,4.55). The longitudinal emittance is 1.17 eVs.

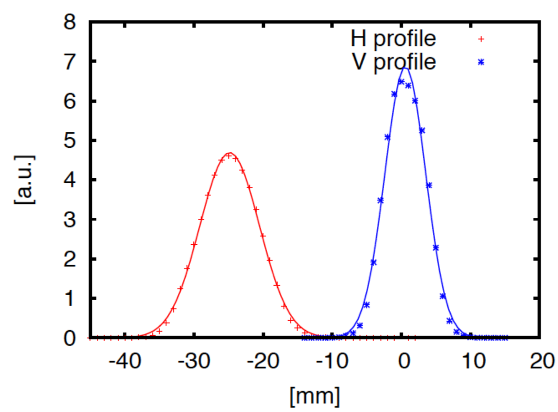

Figure 7: Simulated horizontal and vertical beam profiles after the injection process. Points are the simulations, Lines the Gaussian fits. Same parameters as for Fig. 6.

ACKNOWLEDGMENTS

The authors would like to thank C. Carli, G. P. Di Giovanni, R. Garoby, M. Kowalska, A. Lombardi, M.J. Mcateer, M. Meddahi, F. Schmidt and many other people from the LIU project for useful discussions.

REFERENCES

[1] K. Hanke, "Status and Plans for the Upgrade of the CERN PS Booster", these proceedings, IPAC15.
[2] B. Mikulec, et al., "Tune Spread Studies at Injection Energies for the CERN Proton

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF088

Synchrotron Booster", in Proc. HB2012, MOP249, 17-21 September 2012, Beijing, China.

[3] B. Mikulec, "Performance reach of LHC beams", in LIU Beam Studies Review, 28 August 2012, CERN, Geneva, CH, http://indico.cern.ch/event/200692/.

[4] G. Rumolo, et al., "Expected Performance in the Injectors at 25ns without and with Linac4", in Review of LHC and Injector Upgrade Plans Workshop, 29-31 October 2013, Archamps, FR.

[5] H. Damerau, et al., "RF manipulations for higher beam brightness LHC-type beams", CERN-ACC-2013-0210 (2013).

[6] E. Forest, A. Molodozhentsev, A. Shishlo, J. Holmes, "Synopsis of the PTC and ORBIT Integration", KEK. Internal Report (A), 4 November 2007.

[7] E. Benedetto, et al., "Detailed Magnetic Model Simulations of the H- Injection Chicane Magnets for the CERN PS Booster Upgrade, Including Eddy Currents, and Influence on Beam Dynamics", in Proc. IPAC'14, TUPRI027, Dresden, Germany (2014).

[8] V. Forte, et al., "The CERN PS Booster Space Charge Simulations with a Realistic Model for Alignment and Field Errors", in Proc. IPAC'14, TUPRI029, Dresden, Germany (2014).

[9] V. Forte, et al., "Longitudinal Injection Schemes for the CERN PS Booster at 160 MeV Including Space Charge Effects", these proceedings, IPAC15, 2015.

[10] E. Benedetto, et al., "Transverse Emittance Preservation Studies for the CERN PS Booster Upgrade", in Proc. HB2014, THO4LR05, East Lansing (MI, USA), 10-14 November 2014.

[11] G. Rumolo, LIU target beam parameters, EDMS-1296306 (2014).

[12] J. Abelleira, et al., "Painting Schemes for CERN PS Booster H- Injection", these proceedings, IPAC15, 2015.

[13] J.D. Galambos, J.A. Holmes, D.K. Olsen, ORBIT User Manual Version 1.10, 2011.