TRANSVERSE EMITTANCE PRESERVATION STUDIES FOR THE CERN PS BOOSTER UPGRADE

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Abstract

As part of the LHC Injectors Upgrade Project (LIU), the CERN PS Booster (PSB) will undergo an ambitious upgrade program, 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 rings characterized by similar space-charge tune spreads (about 0.5 at low energy), the peculiarity of the PSB is the small transverse emittance that needs to be preserved in order to provide high brightness beams to the LHC. We here try to identify what is the minimum emittance that can be achieved for a given intensity, via measurements, scaling estimates and simulation studies. The latest are based on our best knowledge of the optics model and take into account known perturbations such as the one induced by the short and fast ramping chicane injection magnets.

INTRODUCTION

CERN PS Booster is the first circular accelerator in the LHC proton injector chain and it is where the transverse emittance is defined.

It is made of four superposed rings and accelerates protons up to 1.4 GeV (it will be upgraded to 2 GeV) for the downstream machine, the Proton Synchrotron (PS).

Currently it has a conventional multi-turn injection of 50 MeV protons from Linac2 and the plan is to replace it with a H^- charge-exchange injection from Linac4 at 160 MeV [1]. These upgrades will allow increasing the beam brightness, i.e. the intensity in a given emittance, for the same space-charge tune spread, to reduce the injection losses, which in the present machine are dominated by the interaction with the injection septum, and to better control the filling of the transverse phase-space.

Particles are injected at a given working point (Qx, Qy) around (4.3, 4.5), to optimize multi-turn injection and allocate the maximum possible space-charge tune spread, which in the PSB is around 0.5. The tunes are then reduced during acceleration, as soon as the necktie gets smaller, down to about (4.2, 4.2) at extraction. Figure 1 shows the working point variation during the ramp for the LHC-type beam discussed in the following section, which is injected at a slightly larger horizontal tune, as a result of beam optimization in operation.

With respect to the production of the high intensity beams, in which the goal is to minimize the injection losses [2], for the LHC beams the challenges are to assure a good quality beam in the three planes and to minimize the transverse emittance blow-up.

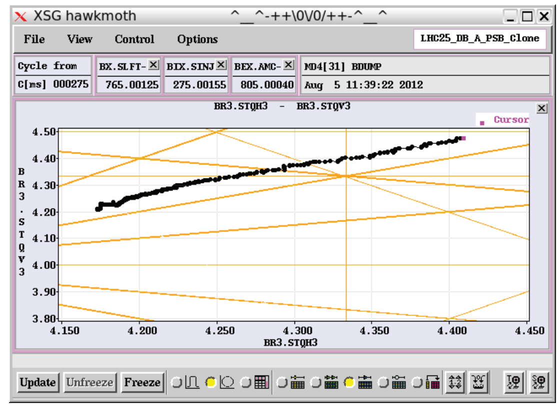

Figure 1: The working point during acceleration of the LHC-type beams goes from around (4.4,4.47) down to (4.18,4.20).

MEASUREMENTS

In 2012 a measurement campaign has been done for the LHC operational beams, with the aim to quantify and define a budget for the emittance blow-up in the entire injection chain.

Figure 2 summarizes the major results for the PSB, i.e. the curve of the average normalized transverse emittance as a function of the beam intensity, at constant longitudinal emittance. The horizontal and vertical emittances have been measured at the extraction flat-top in Ring 3, which featured the best performances, as the result of a careful optimization [3].

Different beam intensities have been produced by increasing the number of injected turns from 1 to 4 and the only other parameter which was slightly changed and optimized for each measurement point was the tune at injection. Two sets of measurements appear in the plot, for different longitudinal emittances, that are 1.20 eVs and 0.86 eVs (matched area), corresponding to the two main LHC beams produced in 2012, i.e. respectively the standard LHC25ns and the BCMS [4].

The first consideration is that the points lie on a straight line on the emittance versus intensity plot; the second is that the slope increases for a smaller longitudinal emittance.

Additional measurements [3] show 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, which induces 10% blow-up during the measurement itself). This indicates that the final values of the transverse emittance

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are dominated by space-charge effects at injection energy and by the multi-turn injection process itself.

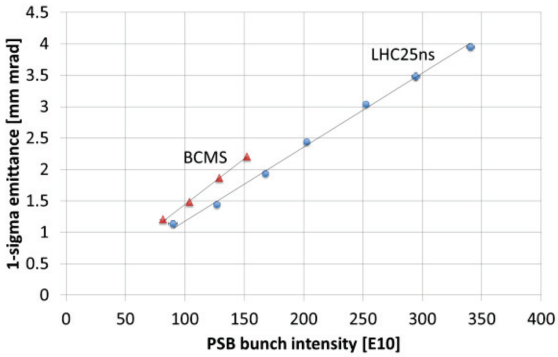

Figure 2: Emittance vs intensity curve for the LHC25ns beam (1.20 eVs) and the BCMS beam (0.86 eVs) [3].

SCALING FOR LINAC4

The future change of injection energy with Linac4 gives a factor $(\beta\gamma^2)^{160MeV}/(\beta\gamma^2)^{50MeV} = 2.04$ reduction of the space-charge tune spread for the present beams.

The baseline of LIU is to keep the same tune spread as of today at the PSB injection [4], and to inject twice as many protons in a given emittance. The other possibility could be to reduce the emittances for a given intensity by the same amount.

With this assumption, the slopes of the lines in Fig. 1 should scale down as $1/(\beta\gamma^2)$, i.e. by a factor ~2. In addition to this consideration, any increase of the longitudinal emittance will help further to decrease the slope.

SIMULATIONS EFFORT

A campaign is ongoing to confirm in simulations the predictions from the scaling estimates. The effort profits from work done in the past and/or for different and specific purposes and includes:

- Code consolidation and benchmarking of the simulation tools with ad-hoc measurements
- Benchmarking of the simulations of the present injection scheme with measurements of operational beams
- Study of the best injection scenario in the transverse and longitudinal plane
- Improvement of the machine optics model taking into account the new hardware

The codes chosen are Orbit [5] for the injection studies and PTC-Orbit [6], i.e. its version with the PTC tracking libraries included, for the longer-term simulations.

Code consolidation and benchmarking with ad-hoc measurements

Measurements have been done in 2012-2013 to analyse space-charge effects in the PSB at 160 MeV, using the special magnetic cycle that was created in the past with an energy plateau at 160 MeV to allow for Machine Development Studies in view of the Upgrade. These are summarized in [7,8] while the results of benchmarking with simulations are presented in [9]. A very good agreement was found in terms of beam losses and profile evolutions in the 3 planes, provided that our best knowledge of the machine is included in the simulations.

In parallel with these studies, a large effort is ongoing within the CERN Space-Charge Study Group to consolidate our simulation tools and to cross-benchmark the different codes. This is the subject of Ref. [10].

Simulations of the present injection scheme

The first attempt to reproduce with simulations the present multi-turn injection is documented in [11]. The injection septum and the slow kickers displacing the closed orbit towards the injection septum have been modelled in Orbit. A good agreement was found for the production of an LHC-type beam with a 2-turn injection, but there were still discrepancies for the other variety of beams that the PSB can produce, especially the ones involving a larger number of injection turns. This can be due to missing ingredients in the optics model and/or to the large uncertainties in the definition of the injection settings, such as offsets in positions and angles and the parameters related to the kickers, i.e. calibration curves to get the strength, and the start timing with respect to injection. Simulations put in evidence how the evolution of beam losses and the build-up of emittance during the injection process are strongly dominated by the presence of the septum and by the injection settings. Moreover, space-charge plays a significant role in this process, therefore needs to be properly taken into account, as it helps in the homogenization of the profiles during injection.

Studies of the best injection parameters

In order to preserve a small emittance during the H^- charge-exchange injection process, the studies aim at optimizing [12]:

- The optics parameters and offsets of the incoming Linac4 beam within the geometrical constrains of the tight space and apertures available in the injection region
- The longitudinal distribution of the incoming beam, assuming no longitudinal painting in order to minimize the number of injected turns
- The painting bump
- The injection working point

Improvement of the optics knowledge and modelling of the new injection hardware

Beam based measurements are ongoing to build up a detailed linear and non-linear optics model of the PS Booster [13]. The final goal is to implement, in a deterministic way, a resonance compensation scheme to accommodate a larger possible space-charge tune spread. Moreover, the outcome of these studies is used in the space charge simulations [9] to provide a detailed set of errors that represent the machine.

Concerning the lattice perturbations induced by the new injection chicane magnets, these are caused by two mechanisms.

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First of all, in order to satisfy the stringent space constraints, short rectangular magnets with a maximum deflection of 66 mrad are required and introduce edge-focusing errors. Since the vertical tune of the machine is close to the half-integer resonance, this induces strong beta-beating in the vertical plane [14]. This effect vanishes as the chicane bump collapses.

Second effect, but of a comparable size, the ramp-down of the magnets within 5 ms induces Eddy currents in the vacuum chamber and generates multipolar components varying with time [15]. This translates again in vertical beta-beating due to the large horizontal orbit excursions inside the magnets, which cause quadrupolar feed-down effects. Perturbations due to Eddy currents depend linearly on the ramp rate and the effects on the beam are proportional to the offset from the magnet center.

To compensate for the beta-beating caused by the rectangular magnets edge effects and by Eddy current induced perturbations, additional trims on the two defocusing lattice quadrupoles QDE3 and QDE14 are envisaged [15].

These magnets and the correcting trims are now modelled in time-varying tables, acquired as input for PTC-Orbit.

EMITTANCE BLOW-UP DUE TO SPACE-CHARGE AND INTERACTION WITH RESONANCES

The aim of these simulations is to identify the minimum emittance that can be achieved for a given intensity.

The errors included in the model are the perturbations at the chicane magnets due to edge effect and Eddy currents. This provides the excitation of the half-integer and 20% vertical beta-beating, which is corrected down to a few % by the special trims on the two lattice quadrupoles, as described above. In addition to that, it induces the excitation 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.

We start with a transversely matched Gaussian distribution, while in the longitudinal plane the distribution is uniform in phase and parabolic in energy spread and evolves in an h=1+h=2 accelerating bucket. Then we follow the emittance evolution versus time for the first 7 ms. The working point is assumed constant and is set to (4.28, 4.55).

The injection process is not simulated, as the focus is on the blow-up during the fall of the chicane (injection is completed within the first 20 μs). Although final simulations should be end-to-end and include the injection painting as well, this approach is here justified by the results of Fig. 3, i.e. that the emittance reached at the end of the chicane bump is independent of the starting value (provided that the final value is larger than the initial one).

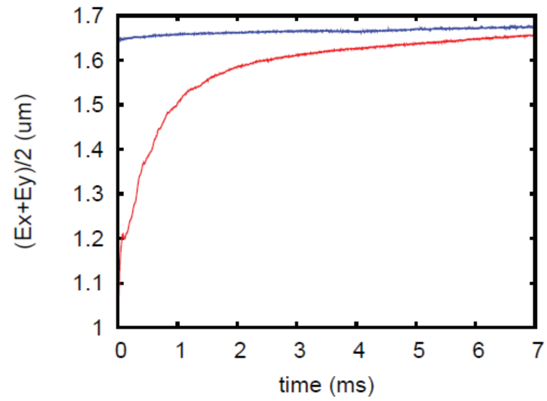

Figure 3: Normalized emittance evolution for 350e10 ppb intensity and a longitudinal emittance of 1.20e Vs, if starting from 1μm emittance or from 1.65 μm at injection.

The results obtained so far, still preliminary, are shown in Fig .4. 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, as discussed in a previous section. The green triangles and the blue crosses show two different sets of data for different longitudinal emittances, respectively 1.17eVs and 1.48eVs. 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. However, the curves have a slope which is a factor 25% smaller, while in our predictions they should have matched.

In order to include other perturbations in addition to the ones at the chicane magnets, the set of quadrupolar errors extracted from the beam-based measurements of 2012 [9] has been added to the model. A first attempt to identify the minimum emittance that can be reached was unsuccessful. The new errors were exciting the half-integer line, which was not compensated and, since the vertical tune was set to 4.55, it caused a large beam blow-up. For our second attempt, we lowered the working point to (4.28, 4.45) so that the space-charge tune footprint could be below the half integer, and the results are plotted as red squares in Fig. 4. Not much difference in terms of emittance blow-up was found with respect to the chicane-only case, apart for a small increase in the vertical plane due to the lower working point which makes the footprint touch the vertical integer.

Figure 5 shows the projections of the horizontal and vertical tune footprint. The initial tune spread for an intensity of 350e10 ppb and a starting emittance of 1μm in both planes is in red. Since it is largely below the integer, blow up occurs mostly in the horizontal plane, and bring the tune footprint to the situation in blue. For comparison, in green is the initial footprint if starting the simulations with emittances of 1.7 μm.

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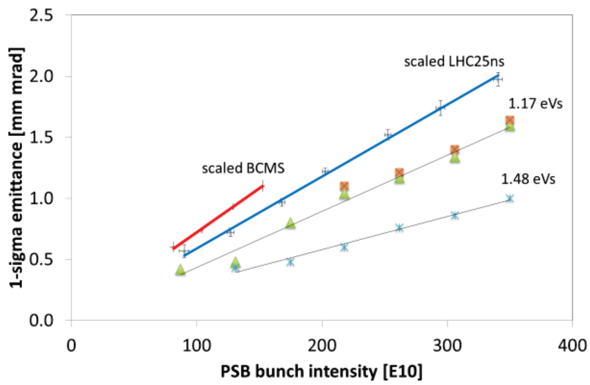

Figure 4: Emittance versus intensity, assuming injection at 160 MeV from Linac4. Blue and Red are the measurements results of Fig. 1 scaled by a factor 2. Green triangles: simulations assuming 1.17eVs longitudinal emittance. Blue crosses: simulations with 1.48 eVs. Red squares: simulations with 1.17 eVs, Qv=4.45 and a more complete linear errors model.

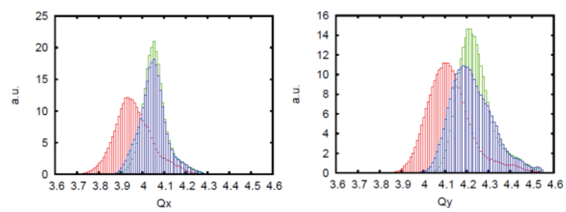

Figure 5: Tune footprint, horizontal and vertical projections: Red: initial tune spread for a beam of 350e10 ppb and 1µm emittances. Blue: final (after 7ms) for the same beam. Green: initial footprint for 350e10 ppb and 1.7 µm. Longitudinal emittance is 1.17 eVs.

EMITTANCE BLOW-UP DURING THE INJECTION PROCESS

Other important sources of emittance blow-up are during the injection process itself, in particular Multiple Coulomb Scattering at the foil, mismatch at injection and jitters and/or ripples in the injection equipment.

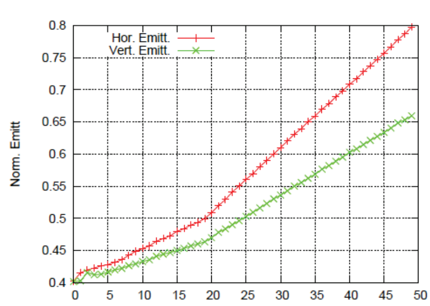

Figure 6: Simulated horizontal and vertical normalized emittance blow-up due to scattering at a 200 µg/cm^2 graphite foil. The multi-turn injection lasts 20 turns and the beam is not removed from the foil after injection has completed. Space-charge is not included.

Figure 6 shows the horizontal and vertical blow-up due to Multipole Coulomb Scattering at a Graphite foil of 200 µg/cm^2. For this exercise we have assumed an injection of 20 turns, without painting, after which the beam is kept on the foil. One can notice the change of slope in the emittance blow-up once injection is completed. Indeed, during the multi-turn injection process, the number of foil traversal per particle is half the number of turns (if no transverse painting is applied). This consideration should be taken into account when evaluating the emittance blow-up with analytical formula, however one should not forget to consider the time needed to remove the beam from the foil, which in our case is of the order of 7 extra foil traversals for the entire beam.

For the simulations shown in Fig. 7, a target intensity of 165e10 protons in a transverse emittance of $\leq$ 1µm has been considered (BCMS type beam). No longitudinal painting is used in order to minimize the number of injection turns. Also no transverse painting is applied, to generate a minimum possible emittance. In ideal conditions, the transfer line optics is matched with the PSB optics at injection (beta functions and dispersion) and no offset is applied between the injected and the circulating beam. A nominal normalized transverse emittance of 0.4 µm is assumed for the beam from Linac4. A uniform distribution in phase (±1.9 rad, corresponding to 616 ns bunch length) and parabolic in $\Delta p/p$ (±1.1e-3, corresponding to an energy offset of ±0.336 MeV) is considered for these studies.

Assuming 40 mA from Linac4, the injection process requires 7 turns injected plus about 7 turns to move away from the foil, implying an increase of transverse emittance of about $\Delta\varepsilon_x$=0.12 µm and $\Delta\varepsilon_y$=0.08 µm.

Figure 7 shows the effect of different injection scenarios, with respect to the ideal case, taking into account injection offsets, mismatch and a larger number of turns, e.g. in case the current from Linac4 would be lower. In particular:

a) Ideal optics and Linac4 current of 40 mA.
b) 25% mismatch of the optics parameters (beta functions and dispersion)
c) Mismatch as in (b) plus a constant offset of 2 mm between injected and circulating beam (steering and/or orbit errors)
d) Mismatch and offset as in (b) and (c) plus Linac4 current limited to 20 mA. This requires doubling the number of injection turns and, as a consequence, of stripping foil crossings.

The result of the simulations, for the different mentioned scenarios, shows a final transverse emittance of ~0.9 µm, still within the target.

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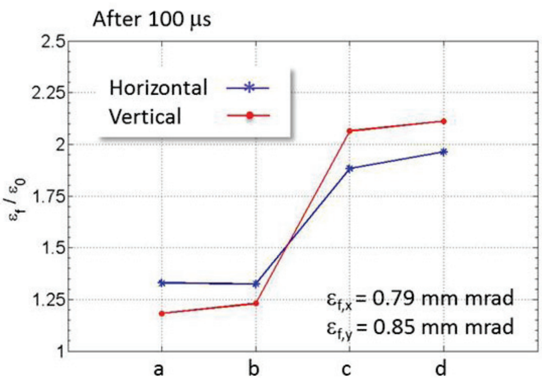

Figure 7: Ratio between final ε_f (after 100 μs) and initial ε_i emittance for different non-ideal scenarios (mismatched optics, orbit offset and reduced Linac4 current). A factor of two emittance blow-up is observed for the most conservative case (d).

CONCLUSIONS

In the present PSB, the emittance is determined by space-charge effects at injection energy and by the conventional multi-turn injection process itself. The relation between transverse emittance and intensity is linear and depends on the longitudinal emittance.

Within the LIU project, the injection energy will be increased to 160 MeV, thus allowing for the injection of twice as much intensity in a given emittance. Moreover the new H^- injection scheme will relax some of the constraints linked to the conventional multi-turn proton injection allowing for more flexibility in the shaping of the emittances. We expect two major contributions in the definition of the transverse emittance: the blow-up due to the injection process itself, e.g. foil scattering and injection errors or ripples, and the space-charge effects at low energy, knowing that the expected tune spread with the upgrade will still be of the order of 0.5.

The effects of blow-up at injection are evaluated for the production of a 1 μm emittance beam, and preliminary results are shown concerning the attempt to verify the scaling (proportional to $\beta\gamma^2$) of the measured curve emittance versus intensity for the Linac4 injection energy. Discrepancies by a factor 25% between simulations and scaled measurements may be due to missing ingredients in the model, i.e. higher order resonances, or simply due to differences in the injection process and/or in the contribution of the dispersion.

In parallel with improving the PSB optics model, efforts needs to be pursued in benchmarking the code with measurements data and in the basic understanding of effects related to space-charge in interplay with resonances.

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