SPACE CHARGE EFFECTS AND MITIGATION IN THE CERN PS BOOSTER, IN VIEW OF THE UPGRADE

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Abstract

The CERN PS Booster (PSB) is presently running with a space charge tune spread larger than 0.5 at injection. Since the High Luminosity LHC (HL-LHC) will require beams with twice the intensity and brightness of today, the LHC Injector Upgrade (LIU) Project is putting in place an upgrade program for all the injector chain and, in particular, it relies on the important assumption that the PS Booster can successfully produce these beams after the implementation of the 160 MeV H- injection from Linac4. This contribution describes the studies (measurements and simulations) that have been carried out to confirm that the PSB can indeed perform as needed in terms of beam brightness for the future HL-LHC runs. The importance of the mitigation measures already in place, such as the correction of the half-integer line, and the effects of non-linear resonances on the beam are also discussed.

INTRODUCTION

The PSB is the first synchrotron in the LHC proton injector chain and it is where the beam brightness is defined. The future increase of the PSB injection energy from 50 MeV to 160 MeV 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 at the PSB injection energy and to inject twice as many protons in a given emittance [1]. In the first part of the paper we summarize the studies that are leading to the beam brightness predictions for the upgrade to 160 MeV, additional details in [2,3]. The simulations, compared with measurements at 50 MeV, are done with PTC-Orbit [4,5]. In the second part we discuss the mitigation measures in place against space charge for both the present situation and the upgrade. Finally we discuss our first attempt to include non-linear errors in our model.

BEAM BRIGHTNESS

Present Machine, 50 MeV p+ Injection

Measurements of LHC beams in the PSB show that, after optimization of the injection settings, the points of the emittance as a function of intensity lay on a straight line [6, 7], indicating that we are running at constant brightness. The brightness here is defined as (Ex+Ey)/2/Np, where Ex, Ey are the normalized rms transverse emittances and Np is the number of protons.

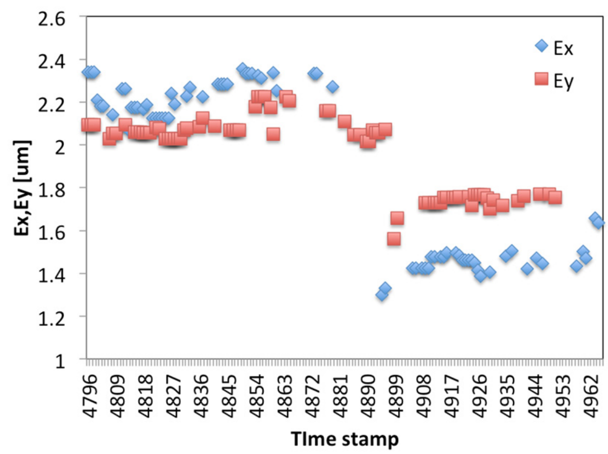

Figure 1: Measured horizontal and vertical rms normalized emittance, averaged over the 4 PSB rings, for Qx=4.28 (<496) and after the change to Qx=4.42 (>496). The vertical tune is fixed at 4.45.

Moreover, in operation we see an important reduction of the horizontal emittance, when the working point is moved from Qx=4.28 to Qx=4.42, as shown in Fig. 1.

In the present PS Booster, the beams emittances are determined by space charge effects and by the multi-turn injection process itself.

In order to prove that the emittances strongly depend on the distance of the working point from the integer lines, we launched PTC-Orbit simulations with a simple model that does not include the proton multi-turn injection process, but only looks at the evolution of an initially matched beam, in a pure linear lattice.

Figure 2 shows the emittance evolution versus time when starting from an initial Gaussian beam of 1.5 µm, for two working points similar to the ones used in operation. We find good qualitative agreement with the measurements. In particular, the horizontal emittance is strongly reduced when going to a larger working point. In this case the vertical emittance is also slightly increasing, since the vertical tune is smaller.

For what concerns the longitudinal plane, the beam is injected in coasting mode and then the voltage of the two RF cavities, h=1 and h=2 (in anti-phase) is raised to V=8kV within 7 ms in an accelerating bucket. This is an important ingredient in the space charge simulations because the bunching factor is going down from 1 to 0.4, thus the line density is increasing. Figure 3 shows the initial and final profiles, from simulations.

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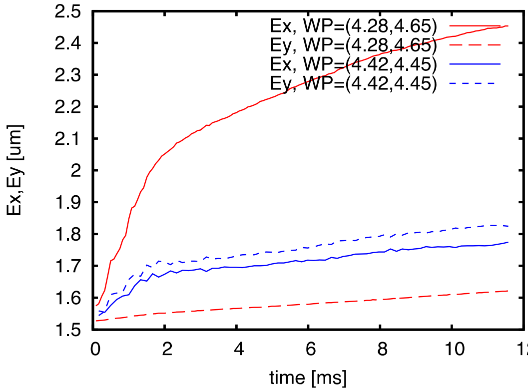

Figure 2: Simulated (simple model) horizontal and vertical rms normalized emittance evolution for two different working points: (4.28,4.65) and (4.42,4.45).

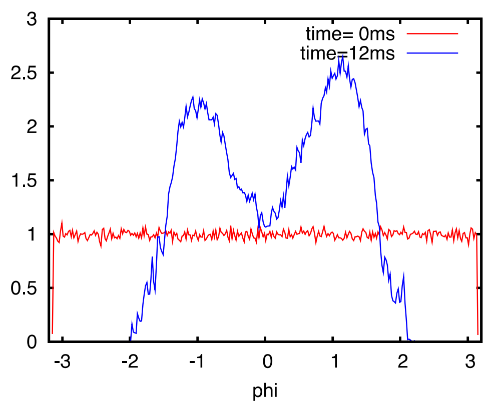

Figure 3: Longitudinal profile at injection (coasting beam) and after the RF capture in double harmonics.

Upgrade to 160 MeV, H- Injection

Applying a simple scaling law, one expects a factor 2 improvement in the PS Booster brightness curve by going from the present 50 MeV injection energy to 160 MeV, to take into account the increase in $\beta\gamma^2$.

Figure 4 shows the emittance versus intensity and the comparison of our simulations with the measurements [6, 7]. The points in red correspond to the two simulations at 50 MeV injection energy discussed in the previous section (Fig. 2), for the working points (4.28, 4.60) and (4.42, 4.45). In green and in orange the simulation at 160 MeV are plotted, assuming the two working points (4.33, 4.55) and (4.43, 4.60), in comparison with the measured line scaled by the factor 2. Raising the horizontal tune increases the beam brightness by reducing the slope of the emittances versus intensity. The curves were obtained for a longitudinal emittance of 1.2 eVs, additional margin will come from an increase of the longitudinal acceptance at injection [2].

The model included in these simulations [2,3] is once more very simple: it does not include the H- charge-exchange injection, but it starts from a matched Gaussian distribution in the transverse planes and looks at the beam dynamics during the fall of the chicane magnets, which takes 5 ms.

Quadrupolar perturbations varying with time are modelled, due to the edge effects and to feed-down effects of eddy-currents induced sextupolar components in the rectangular chicane magnets. To compensate for the beta-beating (and the excitation of the half-integer line), two main quadrupoles at a proper phase advance with respect to the injection region are trimmed with a special function, as described in [8].

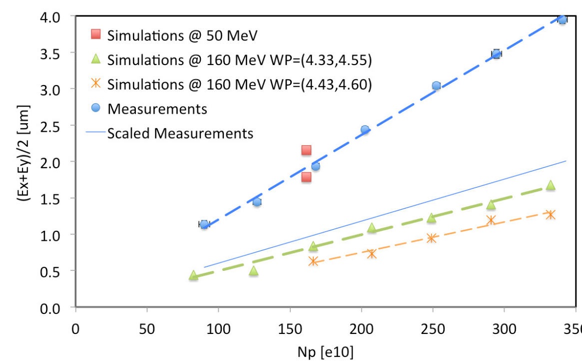

Figure 4: Semi-sum of the normalized rms emittances versus intensity. Blue points: measurements [4]; blue line: measurements slope scaled by 2; green and orange: simulations at 160 MeV injection energy, for two working points; red: simulations at 50 MeV, as in Fig. 2.

Refined Analysis

As a second step, we have included in the simulations the H- charge-exchange multiturn injection, studying different painting schemes [9]. In particular Fig. 5 shows the results of simulations in which the phase space painting is achieved by programming a constant amplitude for the painting bump and by applying an injection offset in both the horizontal and vertical plane.

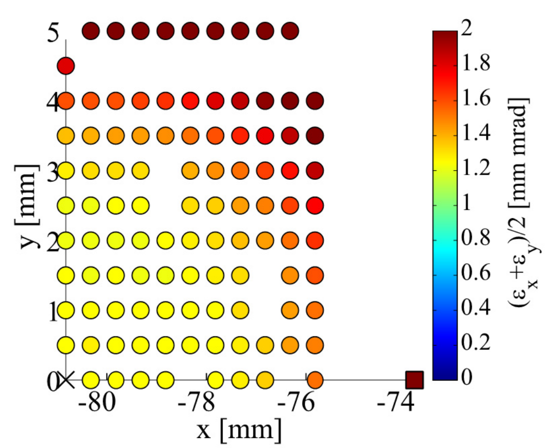

Figure 5: The simulated final emittance (semi-sum of the normalized rms emittances) after 10 ms tracking with respect to the injection offset in x and in y [9]. The beam intensity is Np=3.42e12 and the bare tune is (4.43, 4.60).

The main message from this study is that indeed the details of the injection process are in the shadow of the

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space charge effects and that there is a large span of initial offsets that allow to produce the same transverse emittance. In particular, an emittance of <1.4 μm (the LIU goal is 1.7 μm for an intensity of 3.42e12 protons) can be achieved with an offset of up to 3 mm in both planes. The result is relevant in defining the tolerances with respect to injection offset errors.

MITIGATION MEASURES

Since a space charge tune spread of more than 0.5 [10] is our bottleneck in the brightness of the LHC beams and is affecting losses at low energy for the high-intensity users, the PS Booster relies on several mitigation measures to increase its reach.

RF System

One of the most important measures implemented in the present machine is the use of a second harmonics cavity (h=2) in anti-phase and about the same voltage for the main cavity (h=1) in order to flatten the beam profile and reduce the line density, thus the space charge tune spread.

Presently, the protons from Linac2 are first injected in coasting mode. Then the beam is adiabatically captured and accelerated. With Linac4, thanks to the chopping system, which will remove about 40% of the pulse, the beam will be injected directly into an accelerating bucket, thus reducing the time spent at low energy.

Transverse Painting

The transverse painting in the horizontal plane (and vertical injection offset) is particularly relevant for PS Booster high intensity beams, for which up to 1.6e13 protons have to be injected in about 100 turns [11].

Long term space charge tracking studies [12] have been performed to study the long term evolution of the painted profiles, taking into account the design of a new beam absorber/collimator to localize losses.

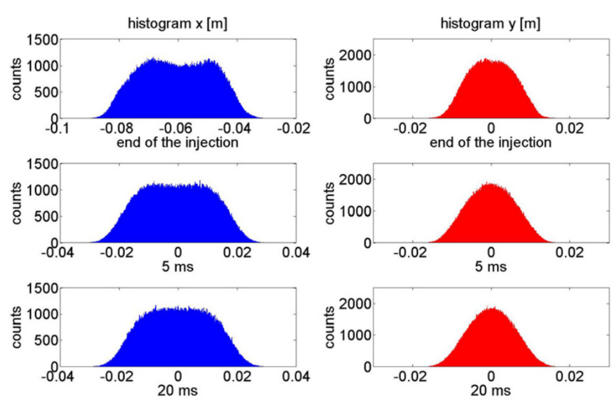

Figure 6: Horizontal (left) and vertical (right) beam transverse distribution at the end of the injection process (~100 μs), after 5 ms and 20 ms. Beam intensity is 1.6e13 protons and the final normalized rms emittances are 13 μm and 6μm.

Figure 6 shows the transverse profile evolution, up to 20ms after injection, which meet the constrains of having a vertical emittance smaller than 6 mm in the vertical plane, imposed by a bottleneck in the extraction line [13], and no more than 5-6% losses at low energy.

Choice of Working Point

The choice of the injection working point is fundamental for the production of high brightness beams, as discussed in earlier in the paper. In the PS Booster, the tunes are varying during the acceleration, from around (4.3, 4.6) at injection down to (4.20,4.20) at extraction.

Today, with the conventional multi-turn proton injection from Linac2, for the high intensity beams which need about 10 turns injected, we are limited in the choice of the horizontal tune, which should be a compromise between the goal to accommodate the largest space charge tune spread and the efficiency of the process itself, i.e. low losses at the septum.

For the LHC beams, for which only 2 injection turns are needed, we already see the advantages of going to a larger horizontal tune, both in measurements and in simulations. With the new H- charge-exchange injection scheme, the constrain of the septum and the one imposed by the Liouville theorem will not be there any more and it will be possible to inject onto the same phase space, at ideally any working point.

Half-Integer Correction

In order to go to tunes above 4.5 in the vertical plane, we need a good compensation of the half integer resonance otherwise strong losses are observed in operation.

We have a dedicated set of normal quadrupoles, powered in pairs with a proper phase advance, in such a way that they form an orthogonal base to correct for the half integer without exciting the integer lines.

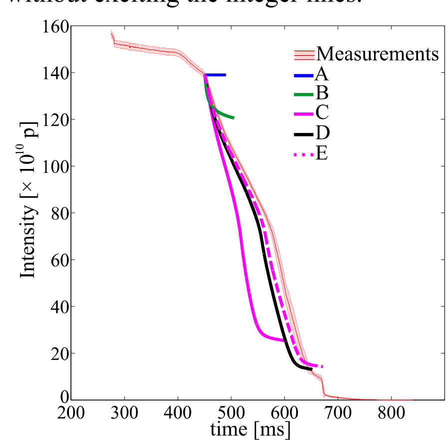

Figure 7: Intensity evolution vs. time. Measurements in pink. Simulation: (A) with only space charge but no errors; (B) no space charge; (C) with quadrupolar errors (programmed Qy =4.53); (D) with quadrupolar and misalignment errors (Qy=4.53); (E) with quadrupolar errors (Qy =4.525).

Figures 7 to 9 show the studies that we did [14, 15] to understand the effect of the half-integer on the beam. A

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special cycle was prepared to accelerate the beam and keep it on a 160 MeV flat-top in order to study the PS Booster at the future injection energy. The beam was brought to a working point of (4.28, 4.53) with the normal quadrupoles correctors switched-on, in order to compensate the 2Qy=9 line. Strong losses occurs when the quadrupoles are switched off, starting at t=500ms from the start of the cycle. The pink line in Fig. 6 shows the measured intensity evolution. One can notice already some losses before, due to the non-perfect compensation that was achieved at the time. The black line is the result of simulations that include the PSB model, at the best of our knowledge, i.e. with misalignments and an effective set of quadrupolar errors [14]. A very good agreement was obtained with the measurements. The transverse profiles stay constant, while in the longitudinal plane one can see (Fig. 7) the equivalent in double harmonics of the bunch shortening phenomena, seen when particles at large synchrotron amplitude interact with a resonance line [15].

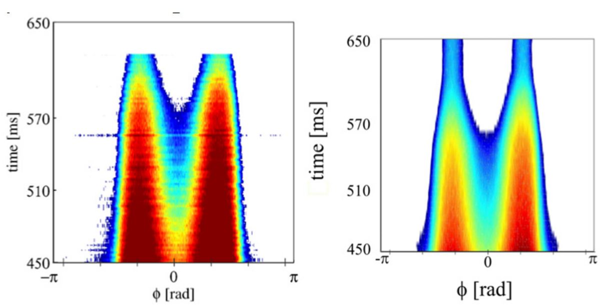

Figure 8: Waterfall plot of the measured (left) and simulated (right) longitudinal bam profile.

Our interpretation of the losses is that particles performing large excursions in the space charge necktie under synchrotron motion interact with the 2Qy=9 line, getting trapped/scattered and eventually getting lost.

As a consequence, the tune footprint shrinks, bringing other particles to interact with the line. The change of slope in the losses, at around t=570ms, also reproduced in simulations, occurs when particles inside the inner separatrix of the double harmonics bucket start interacting with the resonance.

Further studies [16] put in evidence the dependence of the loss rate on the beta-beating, as shown in Fig. 8, where 10 different seeds of errors were generated, with the same standard deviation of measurements.

Non-linear Correctors

A large set of high order multipoles, to correct for normal and skew sextupolar errors, one family of sextupoles for chromaticity correction, one family of octupoles and skew quadrupoles are available in the machine, but only the sextupolar correctors and the skew quadrupoles are used in operation and empirically adjusted to minimize losses for the high intensity beams.

Figure 10 illustrates the extra emittance blow-up in case sextupolar errors are included in the simulations for the 160 MeV brightness predictions.

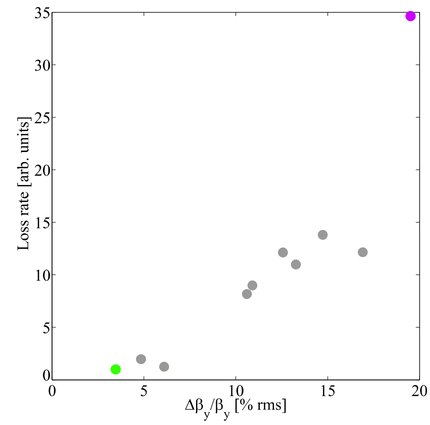

Figure 9: Loss rate vs. vertical beta beating, computed from different error seeds.

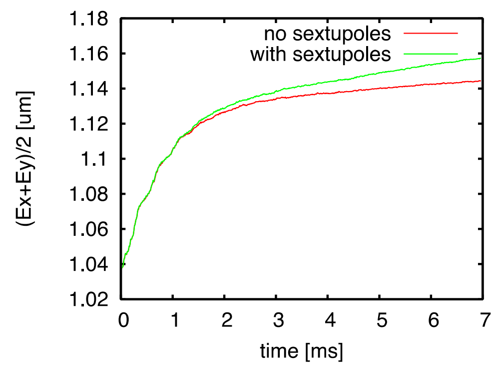

Figure 10: Emittance evolution vs. time, assuming no sextupolar errors in the lattice and with errors. Simulations at 160 MeV, Np=260 e10 p, WP (4.33,4.55).

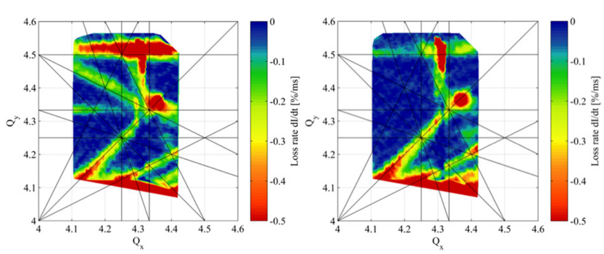

Figure 11: Tune scans. Left, bare machine, Right, after empirical correction [16].

The errors are implemented in our model by powering with the opposite sign the set of correctors empirically found to compensate the lines of Fig. 11 (left). Table 1 lists the resonance driving terms amplitude, as computed with MAD-X, showing that both coupling resonances and integer lines are excited by the sextupolar errors.

Table 1: Driving Terms

Normal		**Skew**	
h3000 =	0.01	h2010 =	0.06
h2100 =	0.06	h2001 =	0.07
h1020 =	0.03	h1110 =	0.17
h0011 =	0.12	h0030 =	0.07
h0002 =	0.04	h0021 =	0.18

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Following this analysis it is interesting to note that the main magnets in the PS Booster carry a non-negligible normal 3rd order component, intrinsic to the dipole itself. In Table 2 the values are listed.

Table 2: Driving Terms Excited by the Main Dipoles

Normal	
h3000 =	0.01
h2100 =	0.02
h1020 =	0.006
h0011 =	0.01
h0002 =	0.02

OPTICS MACHINE STUDIES

Efforts are ongoing to improve the machine model including non-linear terms.

Systematic studies from turn-by-turn Beam Position monitors will most likely be possible from next year onwards, when the electronics will be available. Preliminary analysis of data coming from the few monitors already equipped with turn-by-turn readings has been started. The goal is mainly to commission the hardware and to validate the method of the AC Dipole excitation in a low-energy ring [17].

Measurements of the non-linear chromaticity were made and compared with MAD-X (ptc_normal) assuming a model which includes only the main bends, quadrupoles and the chromaticity sextupoles family. Detailed analysis is ongoing, but a preliminary table showing the comparison are presented in Table 2. By looking at the output of the Control Room application (Fig. 12), one can already appreciate that only the first and second order terms are relevant. Measurements have been taken on the 160 MeV flat-top special machine cycle, for two different working points. The first one is a “standard” one, i.e. (4.20, 4.32), the second one has been prepared in an ad-hoc manner to be (3.32, 3.81). Table 3 summarizes the results, showing a reasonable agreement with the model.

Table 3: Non-linear Chromaticity

Q	Q’	Q”	Measured Q’	stdev
Standard working point				
4.20	-3.35	45	15.1	5.7
4.30	-6.84	87	44.4	13.7
Low working point				
3.32	-2.81	78	48.3	3
3.81	-4.97	116	112	34

CONCLUSIONS

We have shown predictions for the future brightness of the LHC beams in the PS Booster, after the upgrade to 160 MeV, based on space charge tracking simulations being bench-marked with measurements in the present machine. The driving mechanism for the final emittances is space charge related, while the details of the injection process remains in the shadow.

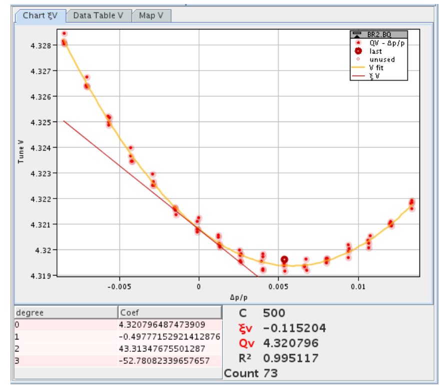

Figure 12: Screenshot of the Chromaticity measurement application in the Control Room.

The PS Booster can count on a series of mitigation measurements and in the paper we have started exploring the impact of the multipole correctors that are available but currently only used empirically. After completing the analysis of the half integer problem we are now moving our focus to the non-linear terms. To do so we investigated the impact of uncorrected sextupolar errors on the brightness curve. Moreover we have measured non-linear chromaticity in order to improve our non-linear model. In the future we expect help from turn-by-turn position measurements that most likely will open the way to more specific measurements.

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