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CERN PS BOOSTER SPACE CHARGE SIMULATIONS WITH A REALISTIC MODEL FOR ALIGNMENT AND FIELD ERRORS

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Abstract

The CERN PS Booster is one of the machines of the LHC injector chain which will be upgraded within the LIU (LHC Injectors upgrade) project. The injection energy of the PSB will be increased to 160MeV in order to mitigate direct space charge effects, considered to be the main performance limitation, thus allowing to double the brightness for the LHC beams. In order to better predict the gain to be expected, space charge simulations are being carried out. Efforts to establish a realistic modeling of field and alignment errors aim at extending the basic model of the machine towards a more realistic one. Simulations of beam dynamics with strong direct space charge and realistic errors are presented and analysed in this paper.

INTRODUCTION

The evaluation of future space charge (s.c.) effects on the beam has to be performed through simulation codes. PTC-Orbit [1] has been selected as tracking code, as it includes the PTC tracking part and the contributions of collective effects (i.e. space charge) through Orbit. To benchmark the code with the measurements, an accurate model of the PSB lattice is necessary, including elements misalignments and magnetic fields errors. To underline the importance of a complete model in combination with direct space charge effects, measurements and simulations are shown in this paper on a 160MeV flat plateau. Two specific cases, concerning a half-integer ($2Q_y$=9) and an integer (Q_y=4) resonance are analysed.

ESTIMATION OF LATTICE ERRORS

The distribution of linear errors in the machine lattice was estimated using the Linear Optics from Closed Orbits (LOCO) method [2]. Orbit response to 13 dipole orbit correctors in each plane, as well as dispersion, were measured, and variable parameters in the lattice model were adjusted in order to minimize the difference between the measured and model orbit response. The initial model used for this analysis contained alignment errors for the triplet quads, bending magnets, and BPM/multipole corrector package stacks as measured in a May 2013 tunnel survey [3].

With the alignment data included, the initial lattice model reproduced rather well the measured off-plane responses, so only the diagonal portions of the orbit response matrix (i.e. no coupling) were used in the fitting. The model parameters used as variables were the strengths of each of 16 defocusing quads and each of the 16 pairs of focusing quads (with the pair of focusing magnets in each triplet treated as a single variable to reduce degeneracy problems in the fitting), and the calibration of the dipole correctors and of the BPMs. The focusing errors, found from the LOCO fitting for the working point (4.20, 4.26), were on the order of one per mil of the nominal integrated gradients of the triplet magnets [4].

THE HALF-INTEGER RESONANCE $2Q_y$=9

Measurements

Measurements of beam intensity, transverse and longitudinal profiles have been performed at a programmed static working point of (4.28,4.53). During the measurement window, from 450ms (referred to as C450) to 620ms (C620), the quadrupolar corrector QNO8L3 has been switched off. However, to reach these conditions, it has been necessary to cross the 0.5 line from below with the corrector ON.

Two different longitudinal bunch settings with a double RF harmonics are considered: 8kV (h=1) + 8kV (h=2) in anti-phase (long bunch), 8kV (h=1) + 8kV (h=2) in phase, (short bunch). Figure 1 shows the intensity evolution during the cycle for both cases.

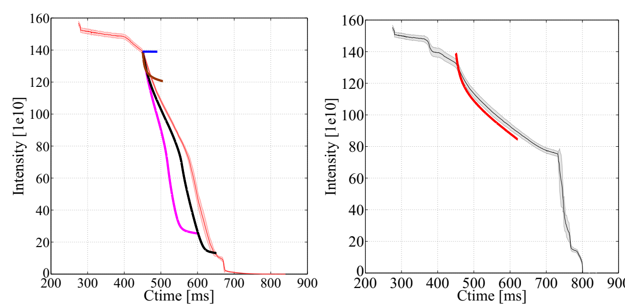

Figure 1: Half-integer: intensities vs time for the long (left) and the short (right) bunch. Red (left) and grey (right) error bands are measurements, the solid lines are simulations.

The losses are evident in the longitudinal plane and concern mainly the large amplitude particles (Fig. 2).
The long bunch presents a different loss pattern with respect to (w.r.t.) the short one: this mainly depends on the different tune spread which brings, in the first case, more particles close the resonance. The short bunch, instead, has bigger spread, so a different (and smoother) loss profile: this allows, for this specific working point (w.p.), to have, at C620, a beam survival of 65% for the short bunch, w.r.t. 15% in case of the long bunch. The beam size, both horizontal and vertical, stays similar over the 170 ms. Figure 3 shows the transverse profiles measurements for the long bunch case, normalized w.r.t. the maximum values, where one can note that the 1σ beam size and the Gaussian shapes are preserved.

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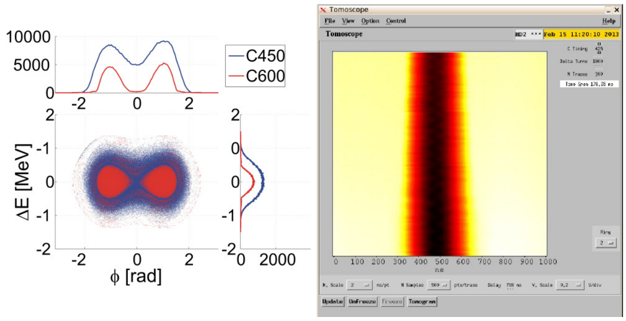

Figure 2: Measured longitudinal phase space at C450 and C600 for the long bunch (left) and waterfall colorplot in the time window [C425-C600] for the short bunch (right).

Simulations

The quadrupolar field errors are necessary to excite the $2Q_y$=9 resonance. The gradient errors, as described, are applied to the lattice after matching it with the programmed tunes (4.28, 4.53) and cause a shift in the bare tune (w.r.t. the programmed one), which is vertically brought closer to the half-integer line (4.285, 4.517). The misalignment errors have also a contribution in the vertical detuning (4.284, 4.513) and in the losses distribution along the machine.

Table1 shows the initial beam parameters and Tab.2 the simulations settings that have been used in PTC-Orbit. To compare the losses profiles for the same starting conditions, the simulated initial intensity and emittance for the short bunch have been put equal to the long bunch, even if they slightly differ in the measurements: this should only marginally affect the quality of the effects confirmed by the simulations in term of profile shapes and quantities.
One should note that all the ingredients need to be included

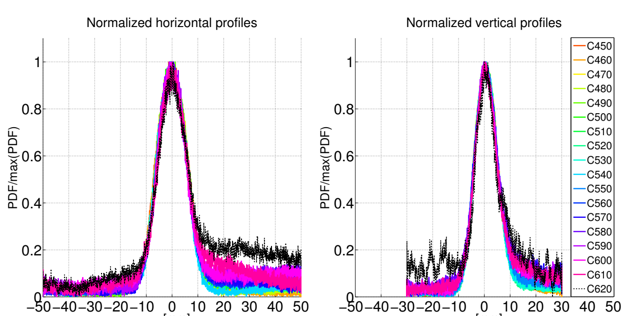

Figure 3: Measured horizontal and vertical normalized transverse profiles in [C450-C620] for the long bunch case.

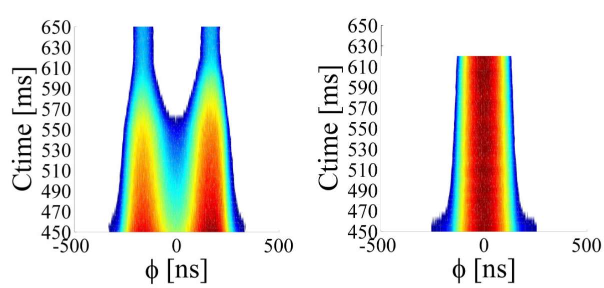

Figure 4: Simulated waterfall plots: the bunch shortening for long (left) and short (right) bunch.

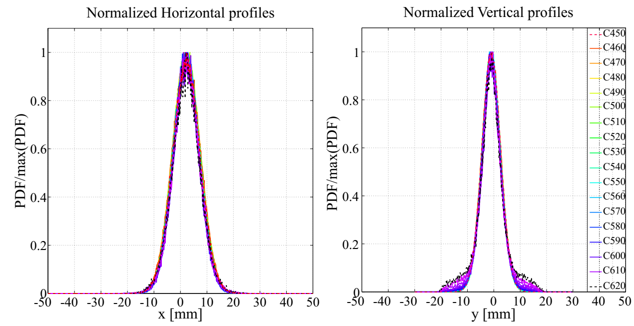

Figure 5: Simulated horizontal and vertical normalized transverse profiles in [C450-C620].

in the simulations. Figure 1 (left) shows that, if no errors are included, s.c. alone does not drive losses (blue line). If errors are included, but no s.c., the losses are due only to chromaticity and saturate (brown line); if only quadrupolar errors, but no misalignments, are included, a qualitative agreement is achieved (magenta line). Finally, if all the errors are considered, there is a significative improvement with also quantitative agreement (black line). The simulated and measured intensity agree both in the dynamic behavior and the steady-state values, including the intensity levels at which the slope change. The losses follow the measurement trend (Fig. 4, left): larger longitudinal amplitude particles are lost at first, before they propagate closer to the +/-1rad longitudinal fixed points. Beam losses and bunch shortening, which are due to resonance crossing and trapping-scattering mechanisms [5], are quantitatively well reproduced also for the short bunch (Fig. 1 & 4, right).

Table 1: Half-integer case - measured initial beam parameters

Initial beam parameters	**long bunch**	**short bunch**
Bunch population [10^{12} p.]	1.39	1.32
σ_x , σ_y [mm]	5.21, 3.6	6.05, 3.67
ϵ^*_x , ϵ^*_y [mm·mrad]	2.64, 2.05	3.24, 2.21
RF voltage (h=1, h=2)	8kV, 8kV	8kV, 8kV
RF cavities relative phase	π	0
Total bunch length [ns]	634	400
Bunching factor	0.44	0.24
Momentum spread (1σ)	1.35x10^{-3}	1.95x10^{-3}
Tune [Q_x, Q_y]	4.28, 4.53	4.28, 4.53
Simulated [ΔQ_x, ΔQ_y]	-0.16, -0.24	-0.27, -0.37

The 1σ Gaussian beam size stays the same along the simulation window and reflects the observed behavior, as Fig. 5 shows in case of 8kV (h=1) +8kV (h=2) in anti-phase. Simulations revealed the formation of tails starting from C600, when the s.c. is weak, and particles are captured into resonance islands (not clear from the measurements).

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Table 2: Simulation Settings

Long. s.c.	ON (128 bins)
Transv. s.c.	2.5D PIC-FFT w/o boundaries
N. of bins [x, y]	128, 128
N. of macrop.	500000
N. of s.c. nodes	201

DYNAMIC APPROACH TO THE Q_y=4 RESONANCE

The second case in analysis is the dynamic approach of the vertical integer resonance. Here, for a short bunch, the tune is moved towards and then far from the resonance (Fig. 6, top). Figure 6 (bottom) reports the measured intensity evolution in case the closed orbit distortion (COD) correction is applied (dashed blue line), or not (solid blue line). In the simulations, in case no errors are added to the model, there are no visible losses (green line), but only emittance blow-up. When the errors are included (black line), the resonance has a rapid and destructive effect on the beam: the function of the programmed tune has been set up to excite the losses only for few milliseconds, in a way to preserve the measurability of the beam in the interval [C500-C570]. The programmed tunes differ from the measured ones due to the effect of the errors. A big contribution to the losses is due to the COD, which increases as the beam approaches the integer resonance. Figure 7 (right) shows that, in case the complete error set is applied, the simulated vertical profile blow-up does not have time to further develop, before the COD provokes the scraping. After C535 (minimum vertical tune), the COD returns small, and so the vertical beam size. It was not possible to measure the transverse profiles through the wirescanners in this situation, so the quantities for the COD corrected analysis have been chosen as starting beam parameters. To benchmark the measured intensity curve with the corrected COD (dashed blue in Fig. 6), a future simulation with the vertical steerers (COD dipolar correctors) is foreseen. Simulations revealed that chromaticity (negative) is, together with the s.c., a relevant component for the tune spread and losses mechanism.

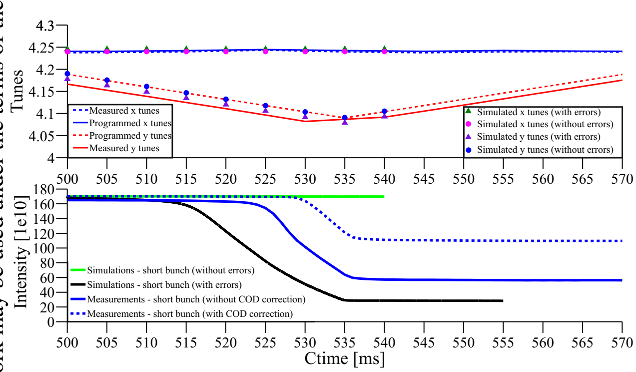

Figure 6: The dynamic approach to Q_y=4: tunes (top) and intensities (bottom) vs time.

Table 3 shows the initial beam parameters (where not specified similar to the short bunch ones in Tab. 1).

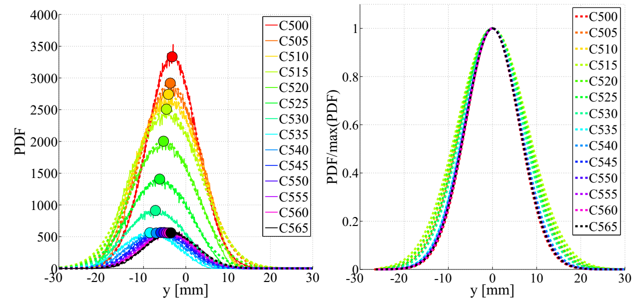

Figure 7: Left: Simulated vertical beam size and COD (circular markers) change. Right: the Gaussian interpolated profiles normalized (w.r.t. the maximum) and centered.

Table 3: Dynamic vertical integer approach - measured initial beam parameters

Initial beam parameters	**short bunch**
Bunch population [10^{12} p.]	1.7
σ_x , σ_y [mm]	5.68, 5.96
ϵ^*_x , ϵ^*_y [mm·mrad]	2.68, 5.05
Tune [Q_x, Q_y]	4.24, 4.19
Simulated [ΔQ_x, ΔQ_y]	-0.24, -0.23

CONCLUSIONS

The combined effect of a realistic set of errors (quadrupolar fields and alignment) and direct space charge has been analysed in a benchmark between measurements and simulations with the PTC-Orbit code in the PSB. Two cases have been taken into account. In the first, concerning a static w.p. close to the $2Q_y$=9 half-integer resonance, simulations showed very good agreement with the measurements for long and short bunch. The second case, concerning the dynamic approach of the Q_y=4 integer resonance, showed the coupled effect of space charge and closed orbit distortion on beam losses. This case has both RMS and COD blow-up while approaching the resonance, but requires further investigations adding the proper set of vertical steerers to the simulated lattice, in a way to obtain the closed orbit correction similar to the one observed in the control room during the measurements. Chromatic corrections are foreseen in future measurements and simulations to disentangle the chromaticity from the s.c. induced tune spreads.

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