INVESTIGATIONS ON CERN PSB BEAM DYNAMICS WITH STRONG DIRECT SPACE CHARGE EFFECTS USING THE PTC-ORBIT CODE

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Abstract

The CERN PS Booster (PSB) has the largest space charge tune spread in the LHC injector chain. As part of the LHC Injectors Upgrade (LIU) project, the machine will be upgraded. Space charge and resonances are serious issues for the good quality of the beam at injection energy. Consequently simulations are needed to track the beam in the machine taking into account space charge effects: PTC-ORBIT has been used as tracking code. This paper presents simulation results that are compared with measurements for machine performances evaluation and code-benchmarking purposes.

INTRODUCTION

The CERN PS Booster (PSB) has the largest space charge tune spread in the LHC injector chain. In order to reduce space charge effects, the LIU project plans to replace the present 50 MeV proton linac (Linac2), injecting in the PSB, with a 160 MeV H^- linac (Linac4). Charge exchange injection will be implemented in the PSB. The increase from the actual 50 MeV injection energy will lead to a factor 2 reduction of space charge tune spread, in principle allowing for 2 times brighter beams. Numerical simulations are needed to evaluate more precisely the expected performance. For this purpose the PTC-ORBIT code has been selected to simulate the beam dynamics under space charge effects and measurements on a dedicated cycle with a 160 MeV plateau have been collected to benchmark the simulations. First results of the benchmarking are presented in this paper.

THE PTC-ORBIT CODE

PTC-ORBIT [1] is a combination between two well known codes: PTC [2] and ORBIT [3]. The 6D particles tracking is made by the PTC code, while ORBIT is used to add space charge and other collective effects. PTC-ORBIT can run on parallel processors and it can handle a number of macro-particles in the order of 10^5-10^6 in reasonable simulation times. Other important characteristics for PSB simulations are:

- possibility to introduce time-dependent elements (magnetic field components, RF cavities) to simulate precisely the injection process;
- the full nonlinear machine model can be implemented through MADX-PTC in which the CERN machine models are built;
- possibility to introduce scattering by a stripping foil (for multi-turn charge exchange injection), apertures, double-harmonic RF;
- several beam diagnostic routines (statistical RMS emittances, 95-99% emittances, momenta, tunes footprint, bunching factor,...).

The code, before being introduced at CERN, has been mainly used for the JPARC Main Ring commissioning [4]. A convergence study based on the behavior of RMS and 95-99% emittances in a “resonance-free” area has been performed [5] to correctly set up the simulations in terms of mesh size and number of macro-particles that have to be tracked by the code.

EXPERIMENTAL SETUP

A special machine cycle has been prepared to accelerate the beams from the present 50 MeV injection energy to 160 MeV (Linac4 injection energy) where they are kept for 220 ms.

For benchmarking purposes, the effect from different resonances has been tested, statically and dynamically:

- Integers $Q_x = 4$ [5] and $Q_y = 4$;
- Half integer $2Q_y = 9$;
- Coupling-Montague (Q_x-Q_y=0 and $2Q_x$-$2Q_y$=0) [5]

The bunch population for the experiments was $1.65\text{x}10^{12}$ p., the same as for the LHC 25 ns beam. A double harmonic RF system was used to flatten the bunch and reduce the Laslett tune spread. Space charge effects have been mainly evaluated in terms of transverse and longitudinal beam profiles, RMS emittances and losses. The machine model used in simulations is linear plus artificial errors for the quadrupolar strengths: the PSB linear and nonlinear model has to be improved. The measurements have been performed in the PSB Ring 2. Table 1 shows the beam characteristics of the measurements close to the horizontal and vertical integer resonances. Table 2 defines some relevant parameters for the simulations with space charge. The Laslett tune spread formulas [6] that have been used are

$$\Delta Q_{x,y} = \frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)[\sigma_x(s)+\sigma_y(s)]} ds,$$

where $\sigma_{x,y}(s) = \sqrt{\beta_{x,y}\epsilon_{x,y} + {D_{x,y}}^2(\frac{\Delta p}{p})^2}$ is one standard deviation of the horizontal/vertical beam size, $\epsilon_{x,y}$ are

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the geometrical transverse emittances (in Tab. 1 $\epsilon^*_{x,y}$ are the normalized ones) , r_p is the classical proton radius; β and γ are the relativistic factors; λ_{max} is the linear density [protons/m]; $\beta_{x,y}$ are the beta functions, $D_{x,y}(s)$ are, respectively, the horizontal and vertical dispersions, and $\frac{\Delta p}{p}$ is the RMS momentum spread. The Laslett tune spread has been kept small enough to avoid the footprint overlapping other low order resonances.

Table 1: Initial beam parameters

Initial beam parameters	$Q_x = 4$	$Q_y = 4$
Bunch population $[10^{12} p.]$	1.65	1.66
$\epsilon^*_x, \epsilon^*_y [mm \cdot mrad]$	4.7, 2.4	4.65, 7.13
RF settings (h=1, h=2)	8 kV, 4 kV	8 kV, 8 kV
RF cavities relative phase	π	π
Bunch length [ns]	688 (long)	634 (long)
Bunching factor	0.4	0.44
Momentum spread (1σ)	1.37x10^{-3}	1.40x10^{-3}
Tune [Q$_x$, Q_y]	4.10, 4.21	4.21, 4.08
Laslett $[\Delta Q_x, \Delta Q_y]$	-0.10, -0.17	-0.09, -0.08

THE HORIZONTAL RESONANCE Q_X=4

Figure 1 shows the measured and simulated emittance evolution. Unfortunately the measurements are affected by large errorbars: this is mainly due to the photomultipliers low voltage settings of the wirescanners, that have been corrected for the following measurements. No significant intensity drop has been observed and no closed orbit correction has been performed. It is possible to appreciate the average increase of 12% after 160 ms in the horizontal plane, mainly happening in the first 10-15 ms. The vertical emittance change is significantly smaller, as expected. The simulations show the same behavior. The agreement is even better if a quadrupolar relative field error in the order of $1‰(1\sigma)$ is taken into account in the simulations.

Figure 2 shows the simulated tune footprint at 115 ms for the $Q_x = 4$ integer resonance with a long bunch.

THE VERTICAL RESONANCE Q$_Y$=4

The optimized photomultiplier settings of the fast wirescanners and the introduction of the closed orbit correction in the Ring 2 allowed to evidence an average emittance growth (always during the first 10-15 ms) of about 27% in the vertical plane, no significant blow-up in the horizontal plane and 2% losses, as shown in Fig. 3. The errorbar is derived taking different measurements (normally 10 for the RMS emittances and 9 for the intensity).

In Figure 3, the model without apertures nor boundaries ($Q_y = 4.08$) shows a clear growth - both in RMS and in 95% vertical emittance, but, as soon as we introduce the complete aperture model of the machine, the statistical RMS emittance growth is almost completely reduced, while the losses behavior follows the 95% value. When

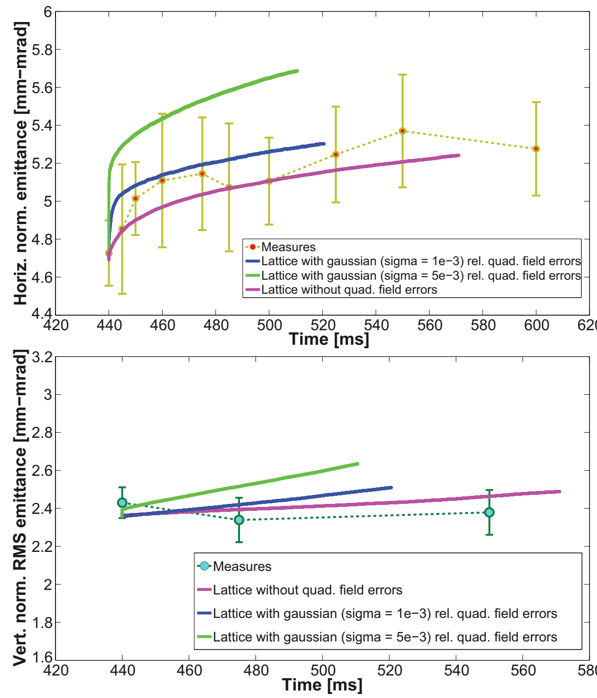

Figure 1: The RMS horizontal and vertical emittances behavior for Q$_x$=4.10 and Q$_y$=4.21.

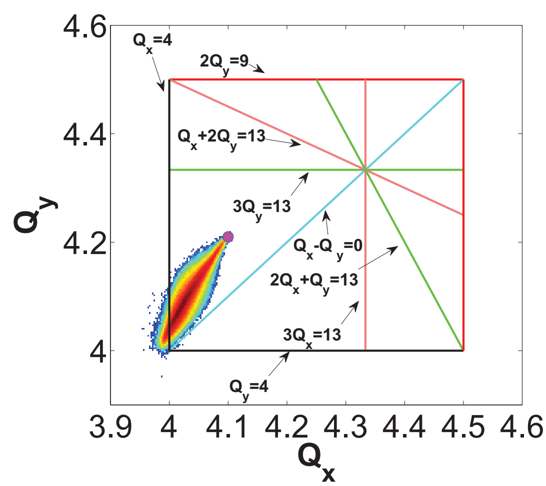

Figure 2: A PTC-ORBIT simulated footprint (after 115 ms) on a tune diagram in the PSB (with a few relevant resonance lines). Purple dot: the lattice working point.

introducing a model of space charge with boundary conditions, the tune footprint shifts towards the resonance as effect of the image charges and the RMS emittance starts growing again. To show how strongly the behavior depends on the tune, another matching has been done with $Q_y = 4.076$ for which the RMS emittance growth ratio is much higher. The vertical tune, along 5 measurements, is 0.0785(+/- 1.3x10^{-3}): in this high tune-sensitive area a small bare tune variation provokes a big blow-up of the vertical RMS emittance, as shown by the simulations presented in Fig. 4.

Table 2: Simulation settings

$Q_x = 4$	
Long. Sp. ch. model	ON
N. of long. bins	128
Transv. Sp. ch. model	2.5D PIC-FFT without bound.
N. of trans. bins [h, v]	64, 64
N. of macrop.	500000
N. of s.c. nodes	201
$Q_y = 4$	
Long. Sp. ch. model	ON
N. of long. bins	128
Transv. Sp. ch. model	2.5D PIC-FFT with and w/o bound.
Boundary shape	Rectangle
Boundary limits	+/- 61 mm; +/- 29.5 mm
N. of trans. bins [h, v]	128, 128
N. of macrop.	500000
N. of s.c. nodes	201

For these simulations, a first attempt to better approximate the quadrupolar errors has been performed, namely by introducing in the MADX lattice a strength for the normal quadrupolar correctors QNO8L3 and QNO16L3 as used in operation to cure the half integer resonance. The relative strength error coming from the empirical settings is around 1.7x10^{-3}, so in the same order of the sigma values used in the previous case. Due to the fact that such an error is localized (no more a zero average random distribution), the tunes change in the third decimal digit (with respect to the matched one): this may as well affect the simulations close to the resonance. The tune values, reported in Fig. 3, are the originally matched ones.

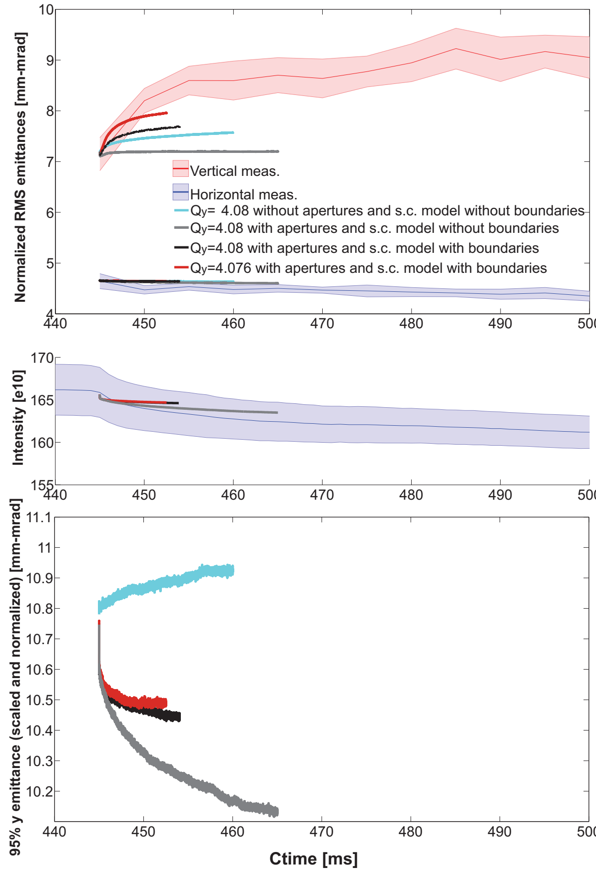

Figure 3: Measurements and simulations close to $Q_y = 4$. The 95% normalized emittance (bottom) is here scaled by a factor 4.

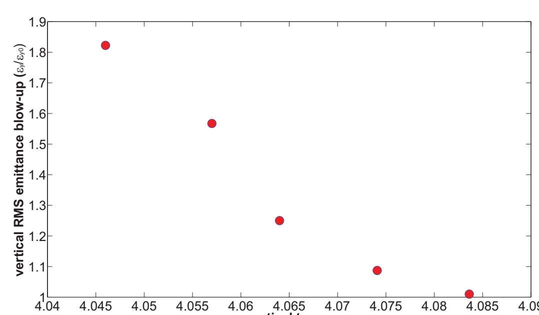

Figure 4: Simulated vertical RMS emittance blow-up vs. vertical tune.

CONCLUSIONS

During 2012 many measurements have been performed on the PSB to understand the space charge phenomena that should be present with the installation of the new Linac4. A set of parameters has been chosen for the tracking, as result of convergence studies. Preliminary simulations, which were presented to benchmark the PTC-Orbit code with the measurements, have been done close to the integers and show qualitative agreement between simulations and measurements. However, a tune variation in the order of 10^{-3} close to these resonances is important and can influence the simulation results. The introduction of the complete aperture model of the machine is important to evaluate the losses. New investigations and simulations are on-going and will continue profiting from the long technical machine shutdown.

REFERENCES

[1] A.Shishlo J.Holmes E. Forest, A.Molodozhentsev. Synopsis of the PTC and ORBIT integration. KEK Internal Report (A), 2007-4, Nov. 2007.

[2] E. Forest and F. Schmidt. PTC - User's Reference Manual, 2010.

[3] J.D. Galambos et al. Orbit user manual, 1999.

[4] A. Molodozhentsev. Operation of the JPARC Main Ring with the moderate beam power: Predictions and observations. ICFA HB '10, THO2B03, p.610, Oct. 2010.

[5] A. Molodozhentsev et al. PTC-Orbit studies for the LHC injectors. HB 2012, WEO1B05, 2012.

[6] B. Mikulec et al. Tune spread studies at injection energies for the CERN Proton Synchrotron Booster. HB 2012, MOP249, 2012.

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