BENCHMARK OF ACCSIM-ORBIT CODES FOR SPACE CHARGE AND ELECTRON-LENS COMPENSATION

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Abstract

Numerical simulation is a possible approach to evaluate and to understand space charge effects in the CERN injector chain for the LHC. Several codes to simulate space charge effects have been developed, and we performed a benchmark of ACCSIM [1] and ORBIT [2] in this study. The study is highly motivated since beam losses and/or deteriorations in beam quality due to space charge effects are not negligible or sometimes considerable in the complex, especially in the Proton Synchrotron Booster. We also discuss a possibility of compensation of space charge effects by applying "electron-lens".

INTRODUCTION

Beam losses and/or deteriorations in beam quality due to space charge effects are not negligible or sometimes considerable in the CERN injector chain, especially in the Proton Synchrotron Booster (PSB). A lot of efforts both from experimental side [3] and analytical/simulation side [4] have been made in order to ensure the best use of injectors toward the LHC. Historically in CERN, the ACCSIM code has been employed for space charge simulation studies. A benchmark study using the ORBIT code has been started to confirm the results from ACCSIM and to profit from the advantages of ORBIT such as the capability of parallel processing. Although this kind of benchmark has been already performed [5], it is still worth to benchmark the two codes using the specific machine parameters of the PSB in which the tune spread is unusually large (up to ~0.5 for high intensity beams and more than 0.3 for LHC type beams discussed here) and overlap with the low order resonances.

We also discuss the compensation of space charge effects by applying a so-called "electron-lens". A new module for ORBIT to introduce electron-lens has been developed. Preliminary results with the module are presented and discussed.

BENCHMARK

Benchmark condition

For the benchmark, a simplified PSB lattice that has 16 identical cells excluding injection bumps is employed. No field error and no alignment error are assumed in the lattice. We assume a proton beam with the kinetic energy of 160 MeV and the intensity of 3.25×10^{12}, which will be provided by the coming Linac4. The beam parameters are summarized in Table 1.

Both ACCSIM and ORBIT are based on the so-called Particle-In-Cell (PIC) method to calculate space charge forces. Simulation parameters such as the number of grids and the number of macro particles should then be carefully determined to minimize numerical noises. In ACCSIM simulations, these parameters have been well defined. We therefore discuss the results from ORBIT for various simulation parameters.

Table 1: Beam parameters for benchmark

*For the benchmark simulations presented here, the beam is captured with an RF system of h=1 with 8kV, whereas in the real machine an RF system of h=2 is used for bunch flattening.

**Coasting beam is used for electron-lens compensation study.

Parameter	**Value**
Kinetic energy	160 MeV
Intensity	3.25×10^{12} proton/ring
Initial transverse distribution	Gaussian / Elliptic
Transverse emittance	2.5 πmm-mrad. r.m.s. normalized
Initial longitudinal profile	Parabolic (bunched)* / Flat (coasting)**
Longitudinal emittance for bunched beam	0.9 eV-s

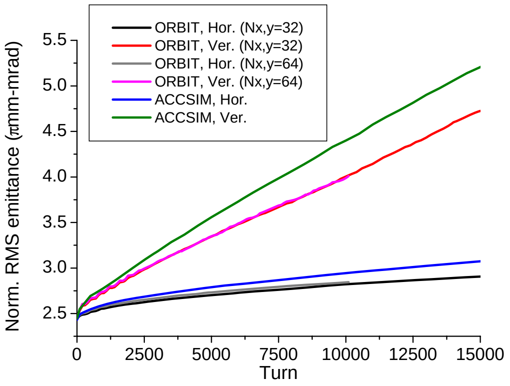
Results

The emittance evolutions for the parameters listed in Table 1 are shown in Fig. 1.

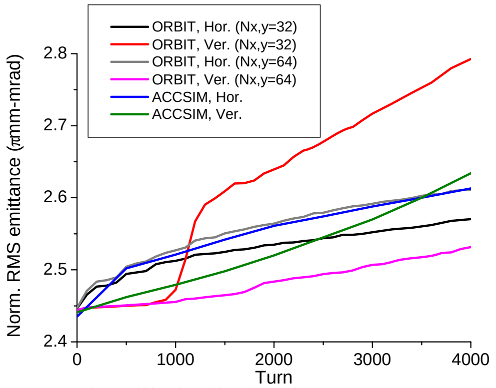
For Gaussian distribution, the emittance evolution does not depend significantly on the number of grid points, and we see rather good agreement between ACCSIM and ORBIT.

For elliptic distribution, especially the vertical emittance growth is sensitive to the number of grid points in ORBIT, and we see a sudden blow-up in vertical emittance. This sudden blow-up is due to generation of halo particles, which is observed both in ACCSIM and ORBIT. It is, however, too small to produce a visible change in r.m.s. emittance in ACCSIM. It is difficult to reproduce such an incoherent motion with different codes. In conclusion, both codes give us fairly similar picture but we have to be careful when we discuss incoherent motions like of halo particles.

Actually, the number of particles of 10^5 is the limit in ACCSIM. Though it is possible to increase it by small modification of the source code, it is practical limit in single processing with the present computation capability. On the other hand, ORBIT could simulate more and more particles with parallel processing. Figure 2 shows emittance evolutions for elliptic distribution and various number of particles.



(a) Gaussian distribution, Np=99999



(b) Elliptic distribution, Np=99999

Figure 1: Emittance evolutions for Gaussian and elliptic initial distribution. Np is the number of macro particles and Nx,y is the number of grid points. (The ACCSIM results are taken from simulations carried out by M. Martini [4])

The number of particle of 10^5 seems not enough in this case, and the emittance evolutions shows signs of convergence with more than 5×10^5 particles.

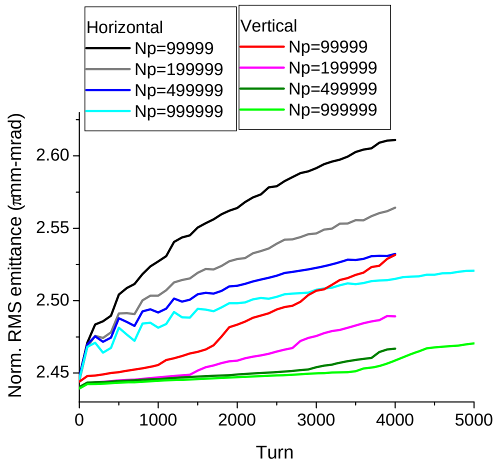


Figure 2: Emittance evolutions with ORBIT for elliptic distribution and for various numbers of macro particles, Np=99999~999999. Nx,y=64.

ELECTRON-LENS COMPENSATION

The idea of electron-lens compensation [6] is to neutralize space charge potential by applying electron-lens (electron beam) to proton beam or possibly to positive ion beam. Ideally the transverse beam profile in the lens should be the same to the one of proton beam to compensate not only linear tune shift but also nonlinear tune spread. Longitudinal profile in the lens is discussed later but it is obvious that the speed of electrons can be different from that of protons, and the energy of electron-lens is generally the order of 1~10 keV.

Localized electron-lens

Since it is impossible to apply electron-lens all over the ring, the electron-lens(es) will be localized longitudinally. The device to generate electron-lens will be a similar to a (low energy) electron cooler. The space charge force due to proton beam and localized electron-lens is sketched in Figure 3.

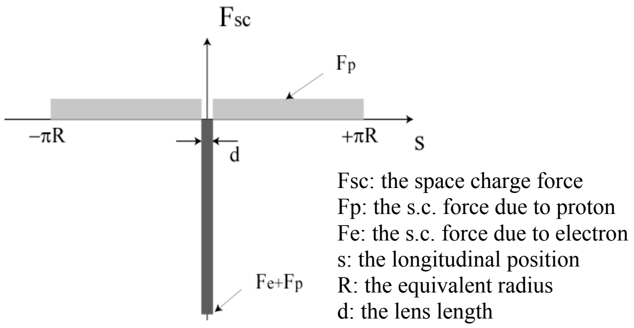


Figure 3: Space charge force with localized electron-lens.

For further convenience, we introduce the following definitions to estimate a required lens current. Since the betatron tune is a consequence of focusing force over the ring, tune shift and tune spread are expected to be compensate perfectly when the following equation is fulfilled for both horizontal and vertical plane,

$$\int_0^{2\pi R} (F_p/\beta + F_e/\beta)\,ds = 0, \tag{1}$$

where β is the horizontal or vertical beta function, which is introduced to take into account effective focusing force. When a costing proton beam is assumed, the transverse densities of proton and electron would be

$$\rho_e(r) = A\rho_p(r), \tag{2}$$

with

$$A = \frac{2\pi R}{d}\,\frac{1-\beta_p^{\,2}}{1\pm\beta_e\beta_p}, \tag{3}$$

where β_p and β_e is the relativistic beta for proton and electron, respectively. Equation (2) means the transverse profile of election beam matches to the proton beam profile. The sign in the denominator depends on the direction of electron beam: it is positive when the electron beam has opposite direction to the proton beam. With Eq.

(3), a required electron current will be a few amperes for the beam of Table 1.

Specifically in the PSB, the proton bunch length (~100 m) will be much longer than the electron lens since the straight section is ~2.5 m. A pulsed electron lens could be applicable to follow the longitudinal profile of proton beam as sketched in Figure 4. Equations (1) and (2) will be fulfilled at one time by applying the pulse-lens.

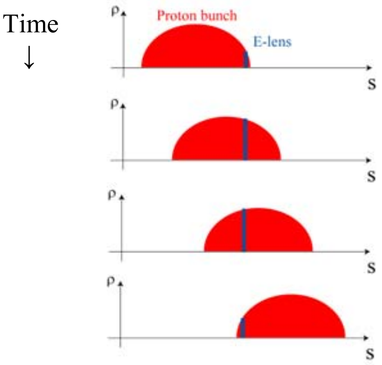


Figure 4: Pulse electron-lens

Modelling of electron-lens

A new ORBIT module to introduce electron-lens has been developed and is under testing. The ORBIT code is written in C++ programming language. Thus it is possible to add user-defined modules without changing the original code (modules).

We introduce the space charge force due to electron-lens through analytical formulae. In other words, we assume the transverse profile of electron beam does not change due to the interaction with proton beam. At this moment, the lens current is constant in time (DC-lens).

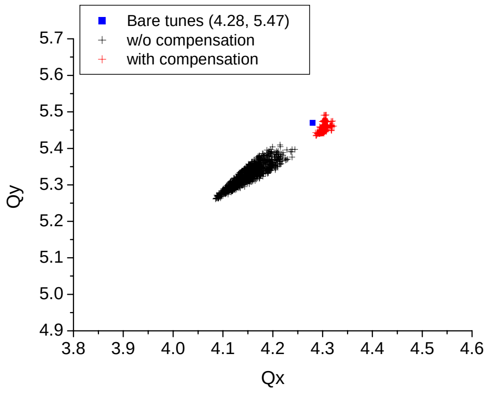
The longitudinal force due to electron-lens is ignored in the module since this would be justified by taking into account a cancellation of deceleration and acceleration at the entrance and the exit of electron-lens.

Tune spread and emittance evolution

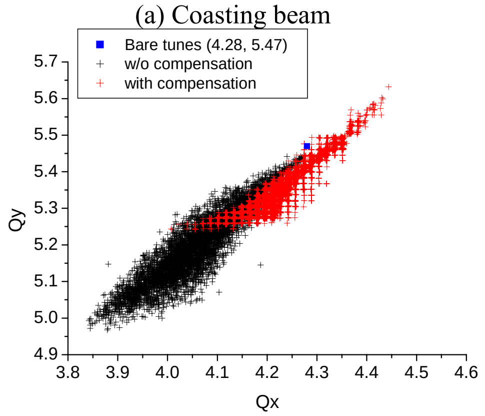
Tune spread is expected to shrink when the electron-lens compensation is applied. To confirm this fact, tune spread is simulated with the module described above. Four electron-lenses with ~2 m long are installed into the PSB lattice so that the super periodicity will be four. The beam parameters listed in Table 1 is again employed, and the results are shown in Fig. 5.

It is seen in Fig. 5(a) that the tune spread is effectively compensated by applying electron-lenses. We confirm the advantage of compensation in principle. In Fig. 5(b), the tune spread of bunched beam cannot be compensated because the electron-lenses are DC-lens at this moment.

Beam emittance directly represents beam quality, and its evolution is practically important to know and to measure the impact of space charge effects. Several simulation results of emittance evolution are shown in Fig. 6.

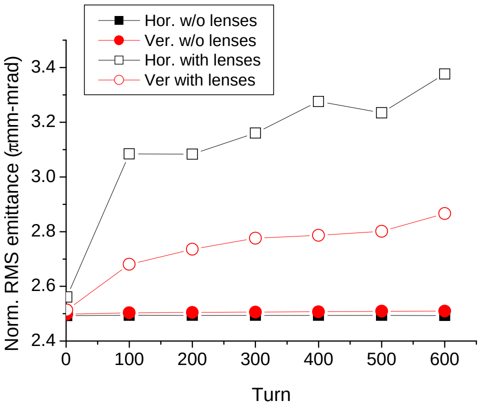


(a) Coasting beam

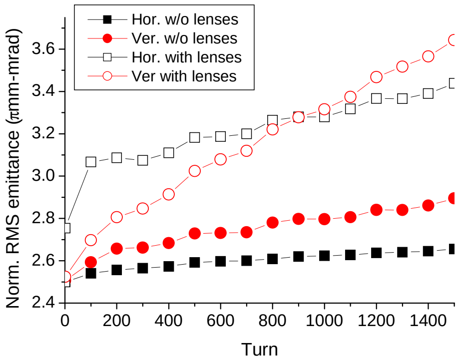


(b) Bunched beam

Figure 5: Tune spread with or without electron lenses.



(a) Coasting beam



(b) Bunched beam

Figure 6: Emittance evolutions with or without electron-lenses.

In the coasting beam, the beam emittances are almost constant as shown in Fig. 6(a) because there seems no obvious source of emittance growth. The beam emittances, however, grow when the electron-lenses are applied. This might be due to the resonances excited by the focusing force of electron-lenses.

Once an rf voltage is applied to the beam, that is, in the bunched beam, the longitudinal motion results in a source of emittance growth. The space charge force depends on line density, and thus incoherent tunes changes in accordance with longitudinal motion. The particles would then experience resonance crossings. Consequently, the beam emittances could growth as shown in Fig. 6(b).

The DC-lenses cannot compensate tune spread of bunched beam but can reduce linear tune shift. As shown in Fig 5(b), the linear tune shift does not cross Qx=4, which is a fourth order structure resonance, when the electron-lenses are applied. At least the crossing of Qx=4 is avoided but the horizontal emittance growth as well as vertical one are enhanced due to electron-lenses.

Unfortunately, all of present results shows that emittance growth is enhanced due to electron lens. However, it would be too early to deny the possibility of electron-lens compensation with the preliminary results shown here. It would be worth trying a pulse-lens, various number of lenses, various operation points as well as different ring and so on.

SUMMARY

A benchmark study of ACCSIM and ORBIT codes has been performed for the PSB ring with 160 MeV beam which will be provided by the coming Linac4. Both codes give us fairly similar picture but we have to be careful when we discuss incoherent motions like of halo particles. We also investigated a possibility of space charge compensation by applying electron-lens. A new ORBIT module to introduce electron-lens has been developed and is under testing. We confirmed that tune shift and tune spread could be compensated by applying electron-lens. Although the preliminary results shows that emittance growth is enhanced due to electron lens, it would be worth trying a pulse-lens, various number of lenses, various operation points as well as different ring and so on.

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