NUAGE, ION CLOUD TRACKER *

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Abstract

NUAGE is a data parallel Matlab code which simulates the ion cloud effect in electron storage rings. The ion cloud is tracked in the ring taking into account the transverse and longitudinal effect of the beam-ion interaction, tracking in magnetic elements, usage of electrodes and gaps as clearing means. This program has been used to compute ionised ion equilibrium state and its neutralisation factor. In this article the NUAGE code is presented. The model, analysis method and performances are discussed.

INTRODUCTION

In an electron storage ring, ions can be produced by ionisation of the residual gas. These ions can induce many sorts of negative effects: emittance growth, reduced beam life time, losses and instabilities like the conventional ion trapping (CIT) [1] and the fast beam-ion instability (FBII) [2]. Several strategies are used to mitigate these effects which can be divided in two types. First type is strategies which concentrate on controlling the instability, like using turn by turn feedback to compensate the beam-ion interaction [3], and mitigating the instability by using sextupole [4] or octupole magnets [5]. A second type of strategy is to focus on diminishing the number of ions causing these effects, which is usually done by combining a number of techniques. The vacuum has to be as good as possible, an effective mitigation is to add gaps in the bunch filling pattern and it is also possible to use clearing electrodes or to use the beam shaking technique [1].

Despite these techniques, several accelerators around the world remain limited because of ion induced instabilities [6]. Even for electron storage rings which are not limited by ions, there are often uncleared pockets which remain and contribute to tune shift and tune spread [1]. For future projects which are currently under design phase, ions are also a important matter like for CLIC [7], or in a smaller scale for ThomX [8]. To reach nominal performances, these projects will need to optimise their means to reduce the ill effects of ions from residual gas. In the frame of ThomX project, a simulation code called NUAGE has been developed to do so.

NUAGE is a data parallel Matlab based program which is designed to simulate the efficiency of the second kind of strategies. NUAGE includes full dynamics of ionized ions: beam-ion interaction, effect of cleaning electrodes and tracking in magnetic elements. This program can be used to reach the ionized ion equilibrium state, locate accumulation points, trapping regions and to optimise clearing means. It also gives the neutralisation factor which can be used to estimate the ion effect on beam dynamics using analytical models or other simulation programs.

NUAGE

Simulation Code

The NUAGE simulation code considers the ion cloud dynamics both in transverse dimensions and in the longitudinal one. The beam-ion interaction model is based on the Bassetti-Erskine formula for transverse part [9] and on the Sagan formula for longitudinal part [10]. This model uses the 'strong-weak' approximation in which ions are considered as a very weak beam which will not perturb the electron beam. In this model, the ion motion is completely determined by the beam Twiss parameters and by the lattice design. Further informations on this model and precisions about the physics are available in [11], in the case of ThomX storage ring.

The main loop of NUAGE is described in Fig. 1, each iteration of this loop corresponds to a duration T_0, which physical meaning depends on the case considered. For a small accelerator with only one bunch like ThomX, T_0 corresponds to the electron period in the ring. For larger accelerator with several bunches, T_0 could correspond to the time between two bunches in a bunch train but it could also be larger or vary depending on the case.

The electric field of DC clearing electrodes computed in an electrostatic solver is used as input to the program. Ions which longitudinal position are near the electrode positions in the ring feel a transverse kick corresponding to the electrode electric field. Tracking in and out of magnetic fields are managed differently, tracking outside of magnetic fields corresponds to a simple integration of the kicks from the beam-ion interaction and the electrodes during the duration T_0. Tracking in magnetic fields (and in curved sections) is done by solving the differential equation of motion in magnetic fields in a curvilinear frame.

Figure 2 shows the general outline of NUAGE code. The program starts with an initialisation of the parameters and of the ion cloud. In NUAGE, all the ions considered are created at the start of the simulation. Usually their positions follow the Gaussian beam distribution in transverse and are distributed uniformly along the ring in longitudinal. A Maxwell-Boltzmann distribution at room temperature is used for their speeds. Generating all the ions at the start of the simulation, instead of considering the ion creation rate, speeds up the establishment of the equilibrium state

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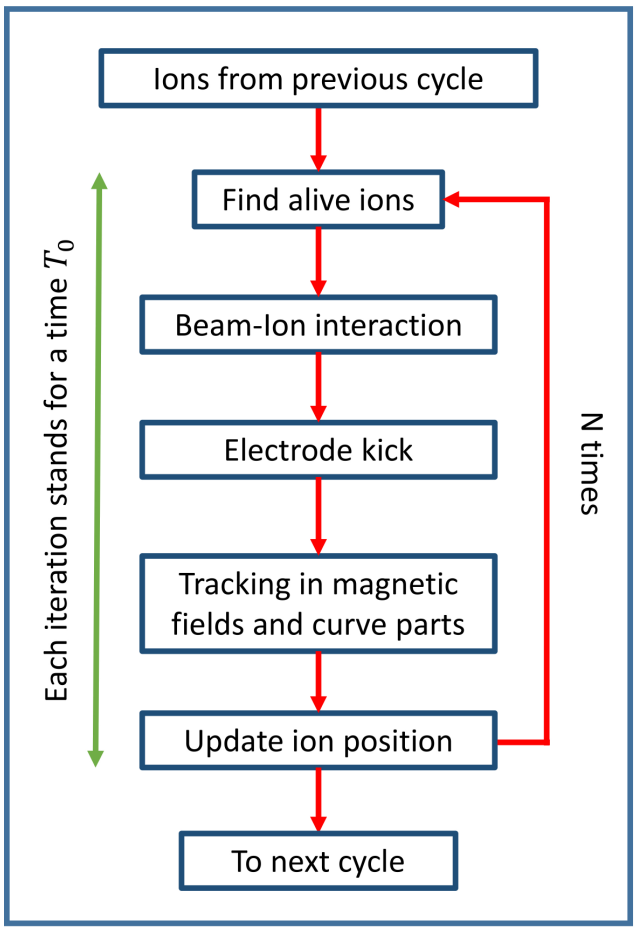

Figure 1: Schematic of the main loop of NUAGE simulation code, corresponding to one cycle.

and allows to compute the clearing efficiency dependence on time.

Then the ion cloud is tracked during the first cycle. A cycle is a number N of iterations of the main loop (Fig. 1) with a determined parameter set: N, T_0 the time between two iterations, switch on/off the beam, switch on/off the clearing electrodes, ... Several cycles can follow each other and a pattern can be repeated. This structure allows to vary parameters in the same simulation to be able to represent many situations. In ThomX storage ring, the electron beam is dumped every 20 ms and there is a variable (approximately 4 µs) injection gap during which there is no beam. Starting from uniform longitudinal distribution of the ions, an alternation of two cycles is used. First cycle is $N = 400000$ iterations of the main loop with $T_0 = 60$ ns with beam on. Then the second cycle is $N = 66$ iterations with $T_0 = 60$ ns without the beam to take into account the injection gap. For a multi-bunch accelerator, it is possible to use this cycle structure to model bunch filling pattern in this way.

Analysis

As the ion creation rate is not taken into account in this type of simulation, it is necessary to do so in the analysis.

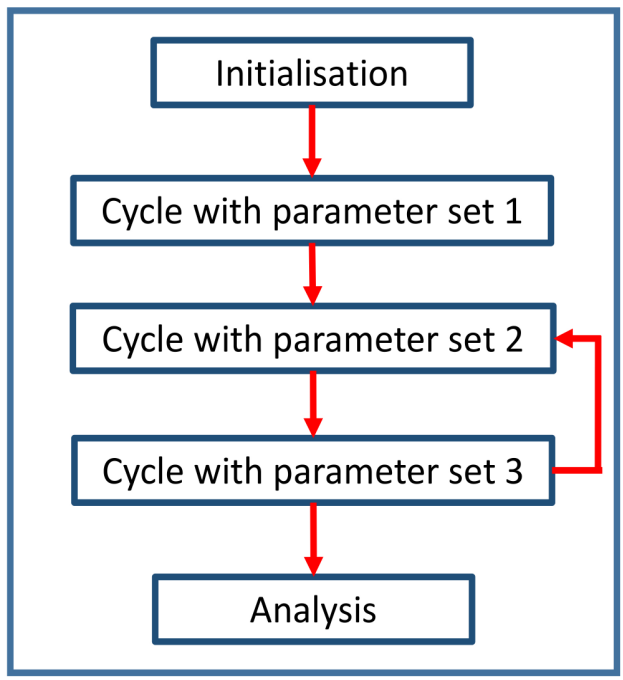

Figure 2: General outline of NUAGE code, using 3 cycles with different parameter set and cycles 2 and 3 alternating.

Once NUAGE has computed the evolution from a starting ion distribution to the distribution after N turn, informations can be extracted from the simulation. Aside form the obvious consideration of the final distribution which gives information about the accumulation points, trapping and equilibrium state it is interesting to extract the clearing efficiency dependence on time. The clearing efficiency can be defined as the ratio of the number of ions $N_i(t)$ over the initial number of ions at the start of the simulation N_{i0}:

$$\epsilon(t) = \frac{N_i(t)}{N_{i0}} \tag{1}$$

This clearing efficiency can be defined for each cycle that the simulation undergo as this value depends on the starting and final distribution and on the parameter set. If C_1 ions are created during the duration T_{0_1} of one iteration of a first cycle (N_1 turns) with a clearing efficiency ϵ_1, then the total number of ions during this cycle is:

$$N_{ions}(t) = C_1 \cdot \int_0^t \epsilon_1(t)dt \tag{2}$$

Using the same notations for ThomX case with 3 cycles gives Eq. (3). As the second cycle is an injection gap no new ions are produced during this cycle and the total ion number after the first cycle is reduced by a factor $\epsilon_2(N_2T_{0_2})$ with $N_2T_{0_2}$ the duration of the second cycle. The third cycle is the same as the first so $C_1 = C_3$ but $\epsilon_1 \neq \epsilon_3$ because the starting distribution of the first cycle is uniform whereas the starting distribution of the third cycle is the final distribution of the second cycle. Thus during the third cycle, ions which were already present at the end of the second cycle will decrease

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$$N_{ions}(t) = \underbrace{\underbrace{C_1 \cdot \left(\int_0^{N_1 T_{0_1}} \epsilon_1(t)dt \right) \cdot \epsilon_2(N_2 T_{0_2})}_{\text{After the injection gap (2nd cycle)}} \cdot \epsilon_3(t) + C_3 \cdot \int_0^t \epsilon_3(t)dt}_{\text{During the third cycle}} \quad (3)$$

This type of approach allows to get the evolution of the neutralisation coefficient, defined as the ratio of trapped charges to beam charges [1], over time which is related to relevant beam dynamics quantities. Furthermore, when the longitudinal equilibrium state of the ions is reached, the clearing efficiency does not change much if the cycles are in a loop and can be considered constant. For instance, for ThomX only 3 cycles were needed to be simulated to get the full evolution of the neutralisation coefficient.

Performances

NUAGE uses Matlab data parallel features to speed up calculation time. Figure 3 shows the variation of the computation time when the different modules of NUAGE are switched on and off. The top plot shows that the usage of the quadrupole module increases the time needed by a factor 1.8 (this factor depends on the ring lattice). The reason for this is that using this module increases the length of the regions where NUAGE tracks particles by solving a differential equation instead of using simple integration. Most of the time, quadrupoles only add small corrections to the ion dynamics. It is only expected to have a major contribution when using combined function magnets [12]. The bottom plot seems to indicate that the simulation is quicker when the electrode module is on. In fact, the time needed to compute this module is very short and as the ions are cleared by electrodes there are less and less ions to track. As the number of main loop iteration increases this explains why using the electrodes modules actually speeds up the computation.

For ThomX case, using the analysis scheme previously presented, only 3 cycles are needed which corresponds to roughly 800 000 iterations of the main loop using 1250 ions per core. This simulation typically lasts about 12 hours instead of the 20 hours expected from extrapolation of the data plotted in Fig. 3 because many ions are cleared and not tracked any more during the simulation.

CONCLUSION AND PERSPECTIVES

The NUAGE code for ion cloud tracking has been presented. Current possibilities features transverse and longitudinal beam-ion interaction, tracking in magnetic elements, usage of electrodes and gaps as clearing means. This program has been used to compute ionised ion equilibrium state and its neutralisation factor, locate trapping regions and to optimise clearing for ThomX storage ring. Further improvement of NUAGE code to take into account multi-ionised ions and beam shaking are under consideration.

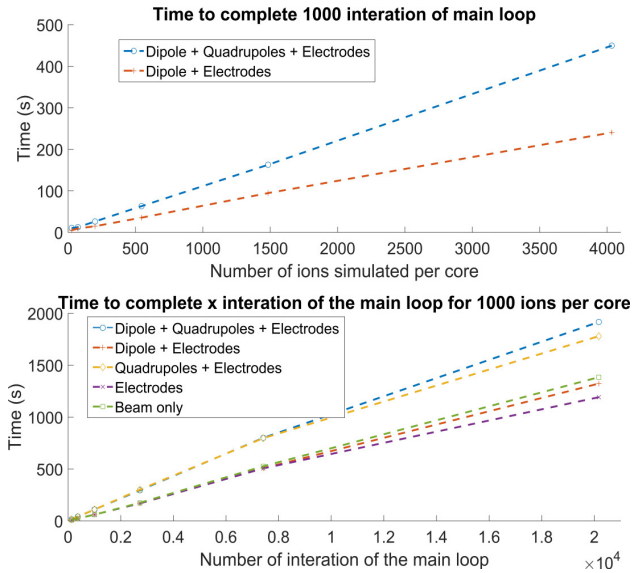

Figure 3: Top plot shows the time needed to compute 1000 iteration of the main loop depending on the number of ion simulated per core for different NUAGE configurations. Bottom plot shows the time dependence on the number of iteration of the main loop for 1000 ions per core for different NUAGE configurations. Computed with PC using an Intel Xeon CPU E5-2630 (8 cores at 2.40 GHz).

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