MAPS FOR FAST ELECTRON CLOUD SIMULATIONS AT RHIC[*]

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Abstract

Luminosity in several colliders, including RHIC, is limited by the electron cloud effect. A careful re-distribution of the bunch pattern around the azimuth of a ring can decrease the average electron density for a fixed total bunch current, allowing the luminosity to be increased. In the search for a bunch pattern that maximizes the luminosity, a fast computer simulation is a key requirement. We discuss the use of fast polynomial maps to simulate the bunch to bunch evolution of the electron density at RHIC. Such maps are empirically derived from existing conventional slow simulation codes.

MOTIVATION

Several computer codes have been successfully developed and benchmarked with experimental observations since the late nineties to study the build up conditions of this effect. A comparison among the different codes was made after the "Eletron Cloud Workshop02" held in Geneva in 2002 [1]. Typically, these codes work either by Particle In Cell methods (like $CLOUDLAND$), or by tracking the electrons grouped in macro-particles, where each macro-particle can join up to a maximum of around 10^5 electrons (like $ECLOUD$, or $CSEC$ [2]). These codes use a considerable amount of CPU time: a complete EC simulation, depending specially on the simulation parameters, can last from around 1 hour to some days. In the cases we studied here (for the parameters seen in Table 1), a single simulation last about 1 hour. In case of a multi-bunch electron cloud, the electric field accelerating the electrons is given by a bunched beam. It is postulated that the evolution of the electron cloud density can be followed using logistic maps. This frees up the detailed simulation codes and enhances physical intuition through the use of standard maths. For a given beam pipe characteristics (SEY, chamber dimensions, etc), the evolution of the electron density, ρ, is only driven by the bunch m passing by, and the existing electron density before the bunch passed by. Following the logistic map formalism, this would be expressed as:

$$\rho_{m+1} = \alpha \, \rho_m (1 - \rho_m), \qquad (1)$$

and the parameter α would be a function of beam parameters, and also a function of the wall surface characteristics of the beam pipe. Note that this is only a mathematical example and we do not give importance to the fact that ρ requires to be dimensionless. Therefore, α would be a

mathematical tool concentrating the EC dependence of the physical parameters. Although the logistic map formalism is finally not appropriate, it illustrates the purpose of this study: simplify the EC problem into a small number of mathematical parameters. In the logistic maps example, the sole parameter is α.

THE BUNCH TO BUNCH EVOLUTION

We then tackle the problem by testing if the existing computer simulations (in this case, $CSEC$ [4]) confirm that the electron cloud evolution can be represented by maps. For this purpose, we center the following studies on the RHIC case. Table 1 shows the physical parameters used for these simulations. Besides the beam characteristics, the SEY behavior as a function of the impinging electron energy is a key parameter in the electron cloud development. All simulation codes are strongly dependent of the model used for the SEY behavior. In this case, $CSEC$ [4] uses the model by described in [3], where one can find detailed explanations of the parameters named in the second part of Table 1. A typical time evolution of the electron density
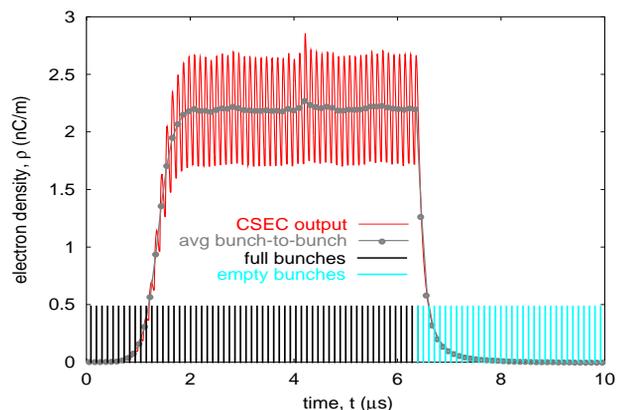

Figure 1: Time evolution of the electron density (red line) computed with $CSEC$ during $10\mu s$ a (RHIC time revolution is $12.82\mu s$). The case corresponds to the injection of 60 successive bunches with a bunch spacing of 108 ns and a bunch intensity of $N = 1.4 \times 10^{11}$ protons (marked with black bars), followed by 60 "empty" bunches (marked with light blue bars). The grey circles mark the average electron density between two consecutive bunches.

has a similar pattern to what is shown in Fig. 1: the electron density per beam pipe meter, ρ, as a function of time grows (initially) exponentially until the space charge due to the electrons themselves produces a saturation level. Once the saturation level is reached the average electron density

does not change significantly. Obviously, in the bunch to bunch evolution, the time step is now integer multiples of the bunch spacing. In Fig. 1 one can see that following the evolution "bunch-to-bunch" does not produce a lack of information about the build-up or the decay time, although the details of the electron density oscillation between two bunches are lost.

Table 1: Input parameters for electron cloud simulations

parameter	symbol	unit	value
bunch spacing	s_b	ns	108
# of bunches	M	...	60
beam radius	r_b	mm	2.4
full bunch length	σ_z	ns	18
bunch charge	N	p $\cdot 10^{10}$	[8-20]
revolution time	t_{rev}	μs	12.82
relativistic factor	γ	...	26
beam pipe diameter	d	mm	60
reflection at energy$\to 0$	R_0	...	0.6
reflection at energy$\to \infty$	P_∞	...	0.2
rediffusion probability	P_{rd}	...	0.5
reflection energy	E_{rf}	eV	60
maximum SEY	δ_{max}	...	2.3
energy for max. SEY	E_{max}	eV	310
energy for secondary e-	E_{sec}	eV	8.9

THE CUBIC MAP

Using the parameters shown in Table 1, the bunch to bunch evolution of the electron cloud density is followed averaging the output of two codes, $CSEC$, for different bunch intensities, N, from $6 \cdot 10^{10}$p to $2 \cdot 10^{11}$ p, in steps of $\Delta N = 2 \cdot 10^{10}$p. Figure 2 shows how the electron density after the bunch m passes by, ρ_{m+1}, behaves as a function of the previous electron density, ρ_m, for different bunch intensities, N. The points in Fig. 2 show the average electron cloud density between two bunches using results from $CSEC$ (Fig. 2). The lines correspond to cubic fits with no constant term:

$$\rho_{m+1} = a\,\rho_m + b\,\rho_m^2 + c\,\rho_m^3 \quad . \qquad (2)$$

Figure 2 is explained as follows: starting with a small initial linear electron density $\rho_0 \neq 0$ (due to beam-gas ionization, beam losses, etc), after some bunches the density takes off and reaches the corresponding saturation line ($\rho_{m+1} = \rho_m$, red trace) when the space charge effects due to the electrons of the cloud itself takes place. In this situation, all the points (corresponding to the passage of full bunches) are in the same spot. The justification of the three terms is explained as a consequence of the linear growth (this term has to be larger than unity in case of electron cloud formation), a parabolic decay due to space charge effects (this term has to be negative to give concavity to the curve ρ_{m+1} vs ρ_m), and a cubic (small) term corresponding to perturbations (electrons generated by residual gas ionization, beam

losses, etc). Reference [6] shows the behavior for (a, b, c) as a function of the bunch charge, N. Reference [7] discusses how RHIC undergoes the electron cloud phase transition from 'off' to 'on' when the coefficient a becomes larger than 1, as the bunch population N increases beyond a threshold value.

The electron cloud decay is described as the succession of bunches with a null bunch intensity, $N = 0$. Neglecting the point corresponding to the electron cloud density after the first empty bunch, the electron density follows a similar decay independently of the initial value of the saturated electron density. It is worth stressing the behavior of this "first empty" bunch, corresponding to the $N = 0$ bunches. The points coming from different saturation values, ρ_{sat} lye off on a general curve, which we call "first $N = 0$", or "first empty bunch" curve. In other words, it takes two bunches to jump from a curve $N \neq 0$ to the decay ($N = 0$ curve). Thus, for the parameters shown in Table 1, the elec-
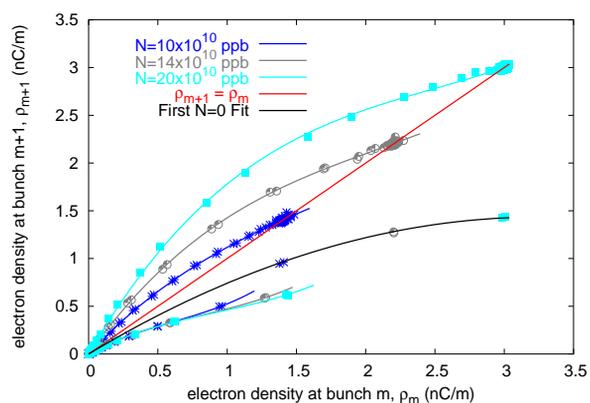

Figure 2: Average electron density after the bunch m passes by, ρ_{m+1}, as a function of the electron density before the bunch m passed by, ρ_m, for different bunch intensities, N. The lines correspond to cubic fits following Eq. 2.

tron density build up for a given bunch intensity is determined by a 3-dimensional vector $\vec{A}(N) = (a, b, c)$, while decay is described by two vectors, one corresponding to the "first ghost bunch", and a second vector for the rest of them.

MINIMIZATION OF ELECTRON DENSITY AT RHIC

After experimental observations during Run-3 [5] it was found that the use of gaps along the bunch train can be useful against the build up of the electron cloud. The goal is to find out a bunch pattern using uneven bunch spacing around the RHIC circumference that does not trigger the electron cloud, or minimizes the detrimental effects of the phenomenon. In the following and as explained in [5], we will use triplets of integer numbers (k_s, k_b, k_g) to describe bunch patterns, where k_s gives the bunch spacing in buck-

ets, k_b the number of bunches filled with that spacing, and k_g the number of "phantom" bunches added, i.e. bunches that are not filled in and therefore create a gap. Changing patterns can then be described by adding a new triplet. When using the 28 MHz RF cavities, RHIC has an harmonic number of 360 buckets, and it is allowed to inject a bunch every 3 buckets (minimum) with an abort gap of 30 buckets. In terms of possible bunches, this implies a maximum of 110 bunches. Reference [5] studies the effect of the bunch pattern on the Electron Cloud and pressure rise. Several $CSEC$ runs were launched with different bunch patterns. We develop a code (MEC, Maps for Electron Cloud) that uses the cubic map formalism to reproduce the results there [5]. As it can be seen in Ref. [6] when reproducing the bunch pattern (3,4,0)(6,8,0), not only it takes two bunches to jump from the curve $N \neq 0$ to $N = 0$, but it also takes two bunches to jump from $N = 0$ to $N \neq 0$. Therefore, the complete algorithm required by MEC to reproduce a given bunch pattern depends on the bunch charge of the bunch m and bunch $m - 1$ passing by:

- "Full" bunches, which in this case denote bunches with charge $N = 8 \cdot 10^{10}$ protons. The cubic form is similar to Eq. 2, and the coefficients are denoted using the vector $\vec{A}_{11} = (a_{11}, b_{11}, c_{11})$.

- "Empty" bunches, which denote bunches with bunch charge $N = 0$. In this case the corresponding cubic form is obtained from the decay case, and it is denoted with the vector $\vec{A}_{00} = (a_{00}, b_{00}, c_{00})$.

- First "empty" bunch, which denotes an empty bunch after a populated bunch, i.e. $N_m = 0$ and $N_{m-1} = 1$. The corresponding cubic form is denoted with the vector: $\vec{A}_{01} = (a_{01}, b_{01}, c_{01})$.

- First "full" bunch, which denotes a full bunch after an empty one, i.e. $N_m = 1$ and $N_{m-1} = 0$. The corresponding cubic form is denoted with the vector: $\vec{A}_{10} = (a_{10}, b_{10}, c_{10})$.

One obtains successful results when comparing the bunch to bunch evolution using $CSEC$ and MEC (see Fig. 3). In Ref. [6], a numerical comparison between the maximum and the average electron line density is done, showing that results computed with the different codes ($CSEC$ and MEC are within a 15% range). While $CSEC$ uses about $\approx 1\ h$ CPU time for each run, MEC is obviously much faster and only uses $\approx 1\ ms$, which represents a speed up of seven orders of magnitude.

CONCLUSION

The multi-bunch electron cloud build-up at RHIC can be determined using a third order polynomial map, written as $\vec{A} = (a, b, c)$. For a given beam pipe, these coefficients are a function of the beam parameters. The dependence of these parameters (a, b, c) on the bunch intensity, N for can
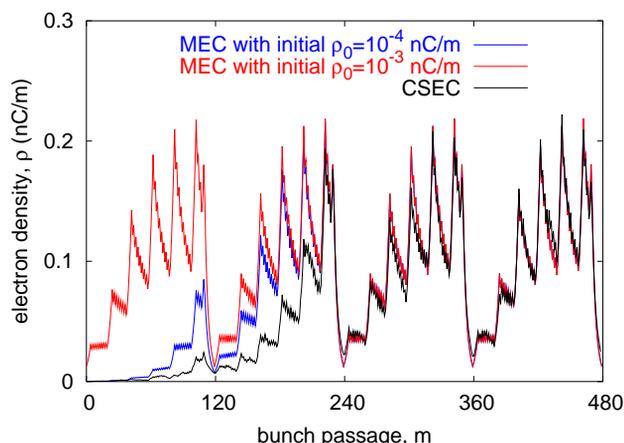

Figure 3: Electron cloud density evolution for bunch pattern (3,4,0)(6,8,0) using $CSEC$ (black trace) and MEC with two different initial electron densities: $\rho_0 = 10^{-4}$ nC/m (blue line) and $\rho_0 = 10^{-3}$ nC/m (red line). No matter the initial electron density, both results agree for the last turn (from bunch passage 360 to 480).

be derived from electron cloud simulations codes. A memory of "two bunches" is found to be necessary when jumping back and forth from full to empty bunches, and therefore a complete algorithm requires four vectors: $\vec{A}_{11}$, $\vec{A}_{10}$, $\vec{A}00$, and $\vec{A}_{01}$. A simulation program, MEC uses these vectors, for example to find out how to minimize the effects of the electron cloud given a machine limitation using alternative bunch patterns. MEC runs up to seven orders of magnitude faster than the current electron cloud simulation codes. In order to obtain a better understanding of the problem, it is desirable to explore how the polynomial coefficients vary as a function of the physical parameters influencing the electron cloud (SEY, chamber dimensions, bunch spacing, bunch charge, et cetera).

ACKNOWLEDGMENTS

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