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SIMULATION OF ELECTRON CLOUD INDUCED BEAM DYNAMICS FOR CesrTA*

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Abstract

This paper provides a comprehensive set of results obtained using the simulation program CMAD. CMAD is being used for studying electron cloud induced beam dynamics issues for CesrTA, which is a test facility for understanding physics associated with electron and positron damping rings. In particular, we take a closer look at electron cloud induced effects on positron beams, including head-tail motion, emittance growth and incoherent tune shifts for parameters specific to ongoing experimental studies at CesrTA. The correspondence between simulation and experimental results will also be discussed.

INTRODUCTION

CMAD is a two species Particle-in-cell (PIC) program capable of studying interactions between beams and electron clouds [1]. A comparison between results from CMAD and other similar codes has been carried out [2] for some simple cases. The parameters used here represent conditions that occurred in CesrTA during experiments being carried out to study the influence of electron clouds on the dynamics of positron beams. Several features such as head tail motion and beam emittance calculations show similar features as to what has already been observed [3, 4].

In observations, we have typically used trains varying from 20 to 45 bunches Depending upon its properties, such as bunch current, bunch spacing, surface properties of the vacuum chamber etc, each bunch creates a certain amount of cloud and as a result the lagging bunches experience a higher cloud density compared to the leading ones. CesrTA instrumentation has the ability to observe the turn by turn position and the beam size of each of the bunches. CMAD tracks a single bunch and so in order to simulate the effect of different bunches along the train, we need to perform a set of independent calculations with varying prespecified cloud densities. The cloud densities seen by the different bunches can be estimated from build up codes or by the observed tune shifts. The tune shifts calculated from build up simulations have agreed well with observed tune shifts [5]. CMAD starts with a uniform distribution of electrons while work is underway to have the program be able to use any distribution as an initial condition.

In the results presented in this paper, we used a 2.08GeV beam, which is the energy most of the experiments have been performed so far. In these simulations, particles are tracked across the full lattice, where each element of nonzero length in the lattice consists of a cloud-beam “interacting point”. Thus, the simulation takes into account the variation of the beam size based upon the beta function and dispersion all around the ring. In the model, the bunch had 96 slices, and the charge from each slice was distributed over a 128 × 128 grid, with 300000 macro particles (positrons) and 100000 macro electrons. The bunch current used was 1mA, corresponding to 1.6×10^{10} positrons. The bunch length was 12.2mm, vertical emittance was 20pm and horizontal emittance 2.6nm. The relative energy spread was 8.12×10^{-4}. The betatron tunes were 14.57 (horizontal) and 9.62 (vertical). The synchrotron tune was 0.055. The chromaticities were 0.6 (horizontal) and 2.3 (vertical) in units of $dQ/(dp/p)$. Overall, care was taken to match the parameters as closely as possible to the machine conditions that existed during the time of one of the observations made at CesrTA.

MOTION OF BUNCH CENTROID

In this section, we show the behavior of the centroid motion for varying cloud densities. The bunch initially had no offset. Nevertheless, the finite number of macro particles, however large, are enough to trigger a self excitation of the centroid motion, that increases with cloud density. A very similar trend in the self excitation has been seen in measurements. Of course, the mechanism of the initial perturbation in the beam offset is different in experiments, *ie* it is not numerical. The self excitation is produced by nonlinear coupling between the two transverse degrees of freedom. In addition, the effect of longitudinal motion would also play a role due to the presence of dispersive coupling between the longitudinal and horizontal motion.

Figure 1 shows the vertical bunch displacement with respect to the initial beam size for varying cloud densities. These show that the extent of self excitation clearly grows with cloud density. In some cases, we also see stages of damping induced by the electron clouds. The oscillation clearly becomes more chaotic as the cloud density increases. The horizontal motion, not shown here is far more stable than the vertical given that the horizontal size of the beam is larger by about a factor of 100.

Figure 2a shows the combined spectrum of centroid motion of each bunch simulated. We see the tunes gradually shifting, along with the sidebands, the appearance of higher order sidebands, and also the splitting of the betatron peak. While the splitting observed in experiments is

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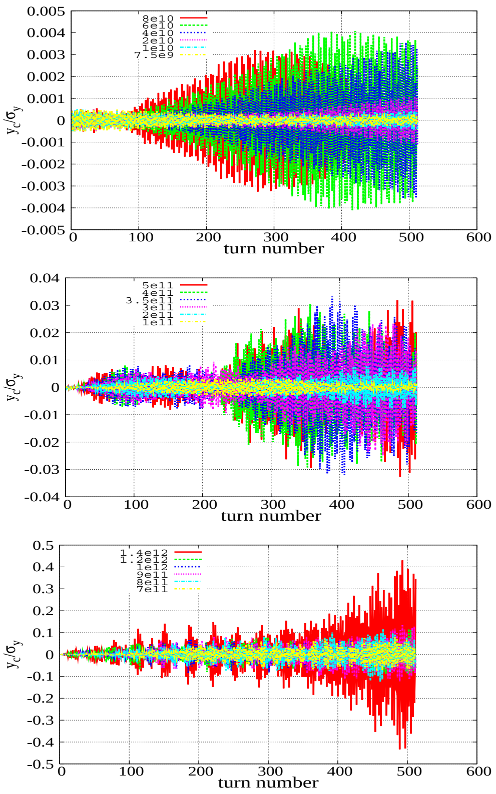

Figure 1: Motion of vertical bunch centroid for varying cloud densities.

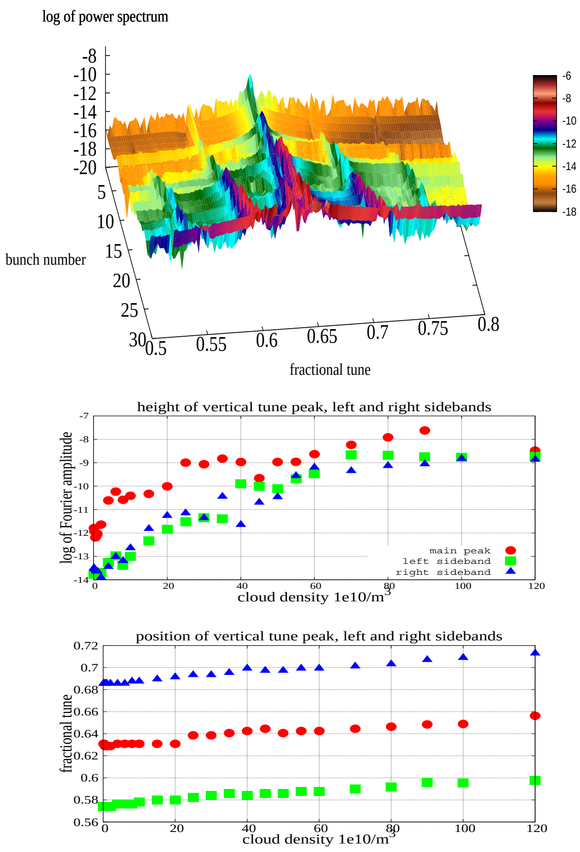

Figure 2: Plots showing the combined spectra of all bunches simulated and the relative heights and positions of betatron and sideband peaks.

different, the rest of the features in this figure bear good resemblance with observations [3, 4]. While the simulations show a secondary peak appearing at the bare lattice tune value, experimental results show the appearance of a secondary peak occurring beyond the main peak. One must note that since CMAD simulates the dynamics one bunch at a time, coupled bunch effects if any, will be absent. Figure 2 also shows a summary of the heights of the left and right synchrotron sidebands off the vertical betatron tune along with the heights of the vertical betatron peaks for the same set of cloud densities. We see that a transition in the relative height of at least one of the sideband peaks occurs at cloud densities of $3.5 \times 10^{11} m^{-3}$ and $4 \times 10^{11} m^{-3}$. For cloud densities beyond these values, we see that both the sideband heights remain relatively close to the betatron peak heights. The figure also shows the position of the betatron and both the sideband peaks in tune space. We see the gradual shift in betatron tune. Additionally, we see that the sideband peaks are consistently spaced away from the betatron peak by the value of the synchrotron frequency. We do not see an evidence of the modes approaching each other as has been seen at KEK [6]. On the other hand, our simulation results are consistent with what has been observed at CesrTA under the same conditions. It is likely that the mode coupling described above would become observable at higher bunch currents and cloud densities. This is yet to be confirmed as to what the conditions at CesrTA should be to observe such a mode coupling.

CALCULATION OF EMITTANCE GROWTH RATE

Figure 3 shows the vertical emittance growth rate. The vertical emittance undergoes a higher growth rate due to its smaller initial value compared to the horizontal emittance, not shown here. In PIC simulations, one needs to worry about numerical noise contributing to emittance growth. Numerical noise can contribute to particles artificially straying away from a stable region to an unstable one. To study this further one needs to perform simulations with varying computational parameters, such as grid spacing, macro particles, and extent of the cloud to get a better quantitative idea of a possible contribution from numerical noise on emittance growth.

Despite the uncertainty in estimating the emittance growth rate, we see a definite increase in this quantity in correspondence with the height of the sidebands which is consistent with observations from X-ray beam size monitors (BSMs) at CesrTA. However, it must be noted that the BSMs measure the beam size after the beam has reached a quasi-equilibrium state, while in simulations we are, in the first 500 turns still looking at a transient state, with the emittance still growing linearly. In order to make a closer comparison between experiments and simulations, one needs to calculate the quasi equilibrium emittance. This would require including the effect of radiation damping and quantum excitations and tracking the beam for several damping times. The damping time of the CesrTA 2GeV configuration is about 21000 turns.

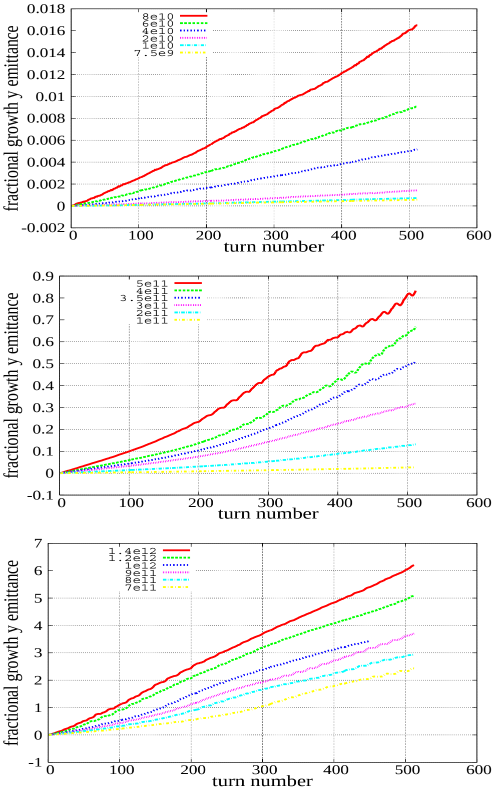

Figure 3: Vertical emittance growth rate for varying cloud densities

MOTION OF INDIVIDUAL PARTICLES

We have observed the motion of individual test particles in order to study their confinement properties for varying cloud densities and also how their oscillation frequency varies with change in oscillation amplitude. Although it would be difficult to determine these quantities experimentally. probing into such details with the help of simulations can provide a lot of insight into the underlying physical processes and the mechanisms that drive the beams unstable in the presence of electron clouds.

In Figs 4, we show the vertical phase space trajectories of particles initially at $x = 0.1 \times \sigma_x$, $y = 0.1 \times \sigma_y$ and $z = 0.1 \times \sigma_z$. The small initial offset ensures that coupling between the three degrees of freedom, if present affects the dynamics of the particle motion. We clearly see that the particles stray away from the ellipse as the electron density increases. The variation of the tune with oscillation amplitude for various cloud densities can in principle be estimated with the help of such single particle trajectories. We plan to extend the analysis of single particle trajectories beyond just phase space traces to computing tune footprints for different cloud densities.

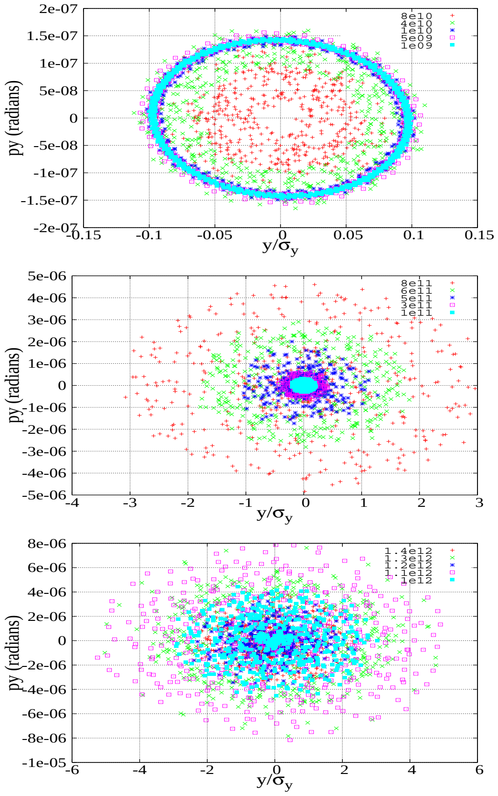

Figure 4: Single particle trajectory in vertical phase space

CONCLUSION

In conclusion, we state that CMAD has been able to reproduce several features of the dynamics of positron beams also observed in experiments. Study was performed for a parameter set corresponding to one set of observations at CesrTA. We need to extend this study to other conditions at which observations have been made and will be made in future. At the same time work needs to be done to include more features in CMAD in order to get a closer quantitative agreement with observations.

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