SIMULATION OF ELECTRON CLOUD INDUCED INSTABILITIES AND EMITTANCE GROWTH FOR CESRTA*

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Abstract

The program CMAD is being used to study single bunch instabilities induced by electron clouds. In the results presented in this paper, we studied the motion of the bunch centroid, the emittance evolution and motion of single test particles within the bunch. A series of studies were performed with varying cloud densities. The spectrum of centroid motion which showed indications of head tail motion was closely examined. The emittance evolution of the beam was computed. The trajectories of single test particles were analyzed qualitatively.

INTRODUCTION

CMAD is a two species Particle-in-cell (PIC) program capable of studying interactions between beams and electron clouds [2]. A comparison between results from CMAD and other similar codes has been carried out [1] for some simple cases. In this paper, we have performed similar simulations with several additional features included. All of them represent the parameters and 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].

In observations, we have typically used trains varying from 20 to 45 bunches with a 14 ns spacing. Depending upon its properties, 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 [4]. 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 non-zero 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 horizontal bunch displacement with respect to the initial beam size. We do not see a significant variation in oscillation amplitude with cloud density. For lower cloud densities, of the order of $1 \times 10^{10}/m^3$ shown in Fig 1a we do not see any significant self excitation. For cloud densities an order of magnitude higher, *ie* $\sim 1 \times 10^{11}/m^3$ shown in Fig 1b there is a clear indication of self excitation. In the next level of cloud densities, Fig 1c, we see that the all bunches get excited to about the same amplitude, but the transient state to reach the final amplitude of oscillation is longer in duration for the lower densities within this category of electron densities.

Figure 2 shows the vertical bunch displacement with respect to the initial beam size. for the same values of cloud densities. These show that the extent of self excitation

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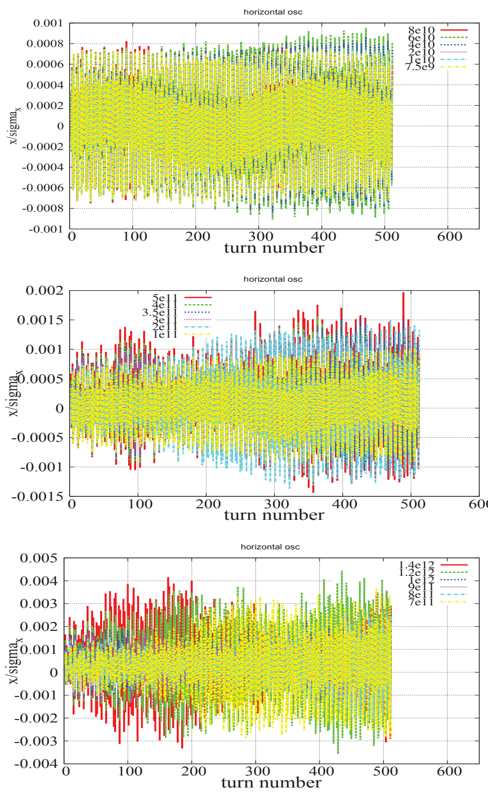

Figure 1: Motion of vertical bunch centroid for varying cloud densities.

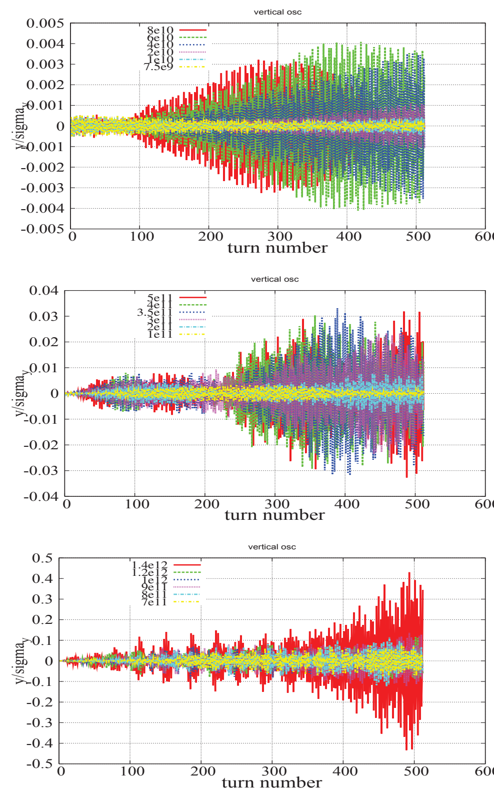

Figure 2: Motion of horizontal bunch centroid for varying cloud densities.

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. It is expected that the horizontal motion is more stable than the vertical given that the horizontal size of the beam is larger by about a factor of 100.

Figures [3,4] show the spectrum of the centroid motion of the bunches under varying cloud densities. In Fig 4, we see that the betatron tune is gradually shifted with increasing cloud densities. The synchrotron sidebands are clearly noticeable, indicative of headtail motion. We clearly see the first order sidebands, which are spaced from the betatron peak by the value of the synchrotron frequency. These represent the so called $m = \pm 1$ mode. Additionally, second order sidebands, spaced by twice the synchrotron frequency value from the betatron peaks are visible at higher cloud densities. These are representative of the $m = \pm 2$ mode of the headtail interaction. We also see that the betatron tune splits with one component remaining at the "unshifted" tune. This splitting has not been observed in experiments, which is likely because the simulations currently do not model the evolution of the electron density in the vicinity of the beam accurately enough. We are currently working toward a more realistic model to account for the density evolution of the cloud during the bunch passage. Figure 3 shows the spectrum of the horizontal motion. We see the presence of synchrotron sidebands, although they are weaker. The tune shift is not visible simply because it is too small and the resolution of the spectra, resulting from 512 turns is not fine enough. It may be noted that while in simulations we are able to isolate the horizontal and vertical motion well enough, observed signals from BPMs always contain a mixture of features of motion from both the transverse planes. Nevertheless, these signals have revealed the same essential features shown by simulations.

Figure 5a shows a summary of the heights of the left and right sidebands along with the heights of the vertical betatron peaks for different cloud densities. We see that a transition in the relative height of at least one of the sideband peaks occurs at cloud densities of 3.5×10^{11} and 4×10^{11}. For cloud densities beyond these values, we see that both the sideband heights remain relatively close to the betatron peak heights. Figure 5b 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. It has been observed at KEK [5] that, due to coupling between lower and higher order headtail modes, the sidebands belonging to the two orders would drift toward each other and even combine into one. 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

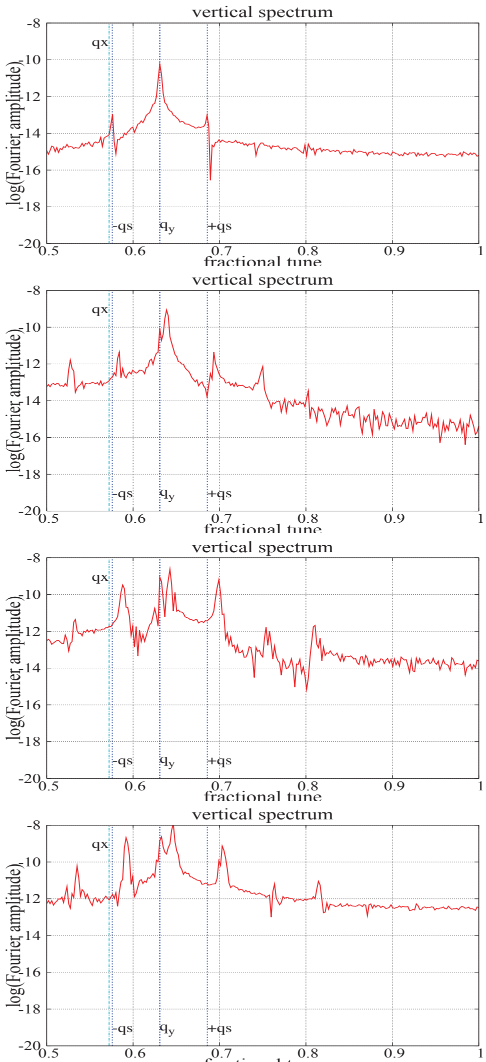

Figure 3: Spectrum of vertical bunch motion for varying cloud densities. From top to bottom (a)6e10 (b)3e11 (c)6e11 (d)8e11 electrons per m^3

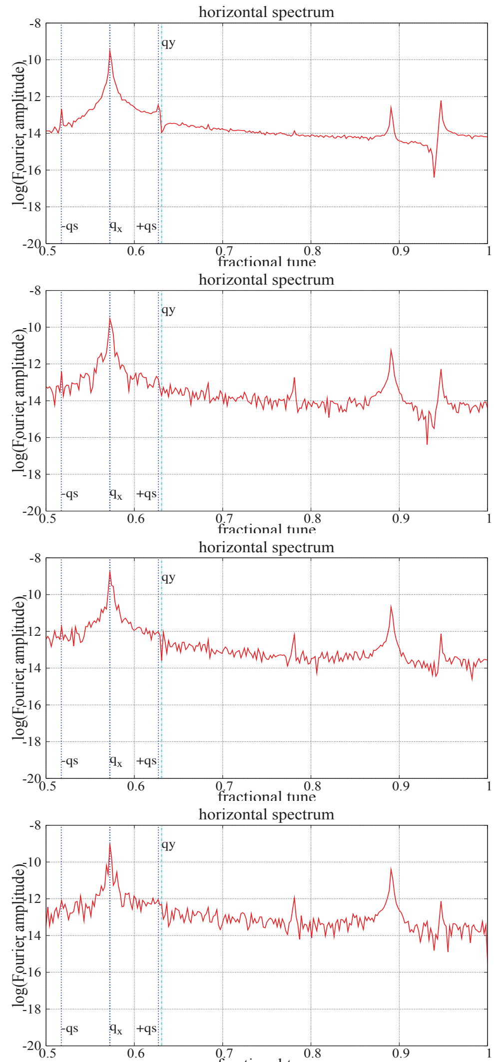

Figure 4: Spectrum of vertical bunch motion for varying cloud densities. From top to button (a)6e10 (b)3e11 (c)6e11 (d)8e11 electrons per m^3

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 [6] shows the horizontal emittance growth rate of the bunches. We clearly see that the emittance growth rate increases with increased cloud density. The horizontal growth rate is very small. At such small values, one might need to factor in a contribution to numerical noise. Nevertheless, we clearly see that the growth rate increases with increased cloud density. Figure [7] shows the vertical emittance growth rate. The vertical emittance undergoes a higher growth rate due to its smaller initial value. One would expect a smaller contribution from numerical noise in this case. In general, we need 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

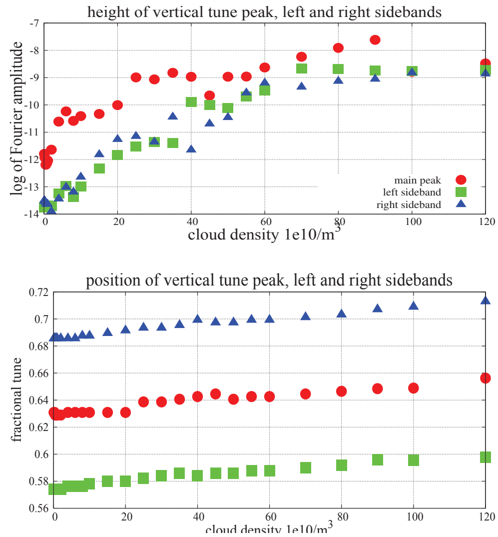

Figure 5: Plots showing relative heights of betatron and sideband peaks (above) and relative position of the peaks in tune space

2GeV configuration is about 21000 turns.

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 8 and 9, we show the transverse phase space trajectory of particles 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. 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.

The horizontal motion, shown in Fig 8 indicates that motion in this plane is fairly regular and lies on the invariant ellipse. On the other hand, in Fig 9 which shows motion in the vertical plane, we clearly see that the particles stray away from the ellipse as the electron density increases. We plan to extend the analysis of single particle trajectories beyond just phase space traces. For example, one could do a frequency spectrum analysis to look for evidence of linear and nonlinear coupling between the respective degrees of freedom, the oscillation frequencies of the so called radial and angular modes for each degree of freedom and several other details associated with single particle motion can also be examined.

CONCLUSION

We have made a systematic study of the influence of electron clouds on the dynamics of positron beams at CesrTA. We have looked into the motion of the beam at different levels of resolution. This included the centroid motion, the emittance evolution and motion of individual particles within the beam. The spectrum of the centroid motion was studied carefully. The spectra of the centroid motion had prominent synchrotron sidebands off the betatron tunes, indicating head-tail motion. The height of the sidebands increased with increasing cloud density and this was accompanied by the appearance of higher order sidebands, especially in the spectra of the vertical motion. Work is underway to examine the motion of individual slices and how they differ according to position along the length of the bunch.

A summary of synchrotron sideband heights for various cloud densities revealed that there was transition in the side band intensity at a density of about $3 - 4 \times 10^{11}$. This has been consistent with observation. It should be noted that in experiments, there is a noise floor that buries the sideband peaks at lower cloud densities, but these are still visible in simulations, where the data has far less noise.

The beam emittance calculation clearly showed that the rate of growth of the emittance grew with increased cloud

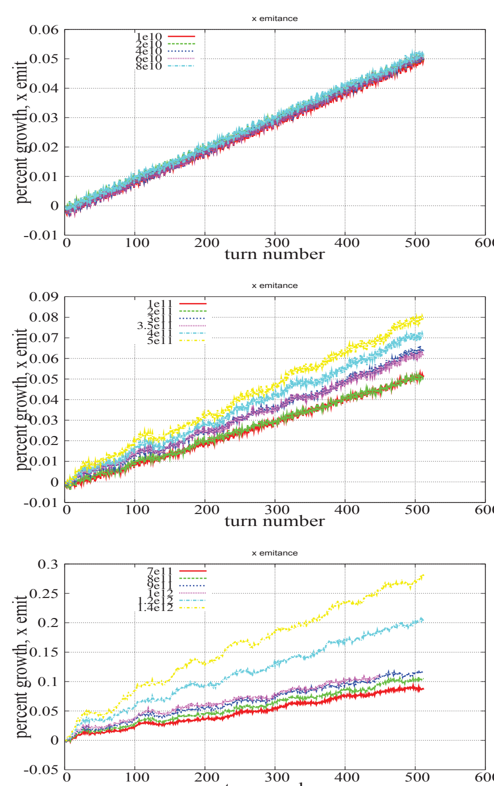

Figure 6: Emittance growth rate for varying cloud densities and a summary of sidebands heights along with the betatron peak heights

density. The growth was always linear, *ie*, a transition to an exponential growth rate was not seen under the given conditions. The simulations were not performed long enough to see see at what values the emittances saturated. It is likely that the final emittance is determined by the influence of radiation damping and quantum excitations, coupled with the electron effect. These additional features are yet to be included in the simulations. It would be challenging to be able to be able observe transient effects in experiments, although such a comparison would be very informative, especially with regard to estimating the contribution of numerical noise in the simulations. If numerical noise is a prominent factor, it will be sensitive to computational parameters such as grid size and number of macro particles. The dependence on these parameters needs to be examined more closely in future. Calculation of the single particle motion showed that the horizontal motion was fairly regular over a range of cloud densities while the vertical motion became increasingly chaotic with increased cloud density.

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

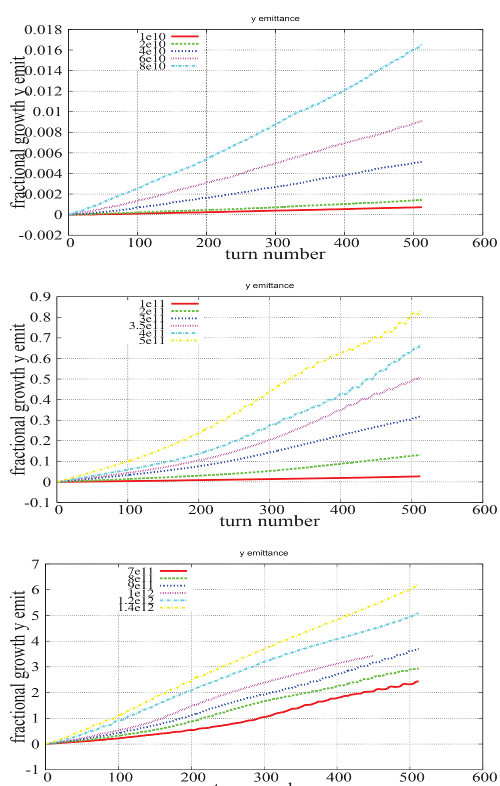

Figure 7: Emittance growth rate for varying cloud densities and a summary of sidebands heights along with the betatron peak heights

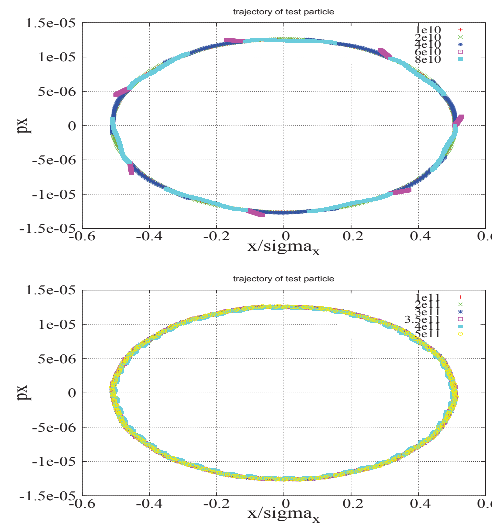

Figure 8: Single particle trajectory in horizontal phase space

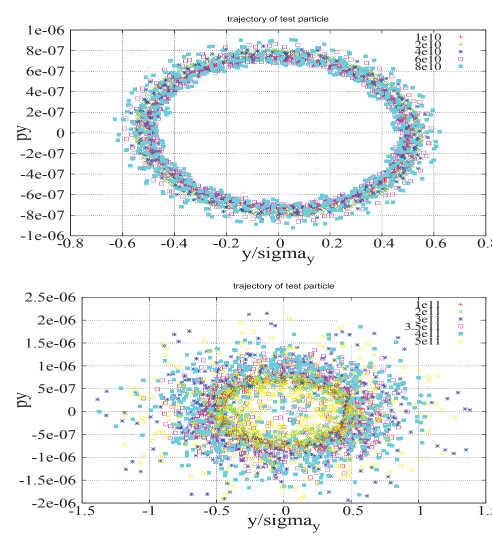

Figure 9: Single particle trajectory in vertical phase space

more features in CMAD in order to get a closer quantitative agreement with observations.

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