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Electron Cloud induced instabilities in the Fermilab Main Injector (MI) for the High Intensity Neutrino Source (HINS) project*

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Abstract

The electrostatic particle-in-cell code WARP is currently being expanded in order to study electron cloud effects on the dynamics of the beam in storage rings. Results for the Fermilab maininjector (MI) show the existence of a threshold in the elctron density beyond which there is rapid emitance growth. The Fermilab MI is being considered for an upgrade as part of the high intensity neutrino source (HINS) effort, which will result in a significant increasing of the bunch intensity relative to its present value, placing it in a regime where electron-cloud effects are expected to become important. Various results from the simulations using WARP are discussed here.

INTRODUCTION

Modeling the electron cloud phenomena comprises of two important components. One of them is the build up process and the other is studying the effects on the dynamics of the beam. This paper will discuss details of the latter part of such a modelling effort. The procedure is applied to the Fermilab maininjector (MI) The study of the build up and exprimental observation for the MI can be found in Refs. [1] and [2].

Electron clouds can affect the dynamics of the beam in different ways. They lead to focusing terms that give rise to a tune shift and also a tune spread. The cloud induces a head-tail interaction due to pinching of the electron cloud which causes coupling of small offsets between the head and the tail of the bunch. Although the effect is essentially a single bunch phenomenon, it occurs in multi-bunch operation since the buidup process is related to multiple bunch passages.

MODELING OF ELECTRON CLOUD EFFECTS ON THE BEAM

WARP is a simulation program that has been developed at LLNL and LBNL for studying phenomena in heavy ion fusion experiments. This is a 3-D electrostatic particle-in-cell (PIC) code that can also run in parallel on multiple processors. Currently WARP is being expanded in its application to study self consistent effects in storage rings, and in particular, the effects of electron clouds on the dynamics of the beam. The features that have been developed into WARP [3] are based on the scheme already implemented into the codes HEADTAIL [4] developed at CERN, and QUICKPIC [5] developed at UCLA. The scheme involves modeling the beam space charge in the form of a series of slices, each of whose charge distribution is deposited onto a series of corresponding two dimensional grids. On the other hand, the electron cloud distribution is deposited on to a single two dimensional grid. The beam is made to pass through the electron cloud ”slice by slice” and the charge distribution of the electron cloud is evolved accordingly. The electrostatic potential due to the electron cloud is calculated for each such electron cloud-beam slice interaction and the resulting field then distributed over the beam is used to push the particles comprising the beam. A schematic of the simulation model is shown in Fig. 1. This set of interactions can be chosen at any number of points in the storage ring which are referred to here as “stations.” The evolution of each particle between two adjacent stations is determined by a transfer map that is valid for the motion of a single particle.

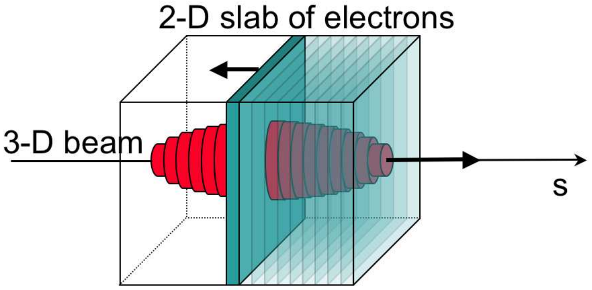

Figure 1: A shematic of the electron cloud - beam interaction in the quasistatic model.

RESULTS FOR THE MI PARAMETERS

The MI is proposed to undergo an upgrade which involves a considerable increase in beam intensity. The upgrade is intended for using the MI as a high-intensity neutrino source. The machine ramps the proton energy from 8.9 GeV at injection to 120 GeV at extraction, and in the process undergoes transition. In this paper, we present results corresponding to the injection parameters only. A list of parameters representing the beam and machine parameters is given in table 1. These parameters represent the conditions under which simulation studies are presently being carried out and some of the numbers may change as this

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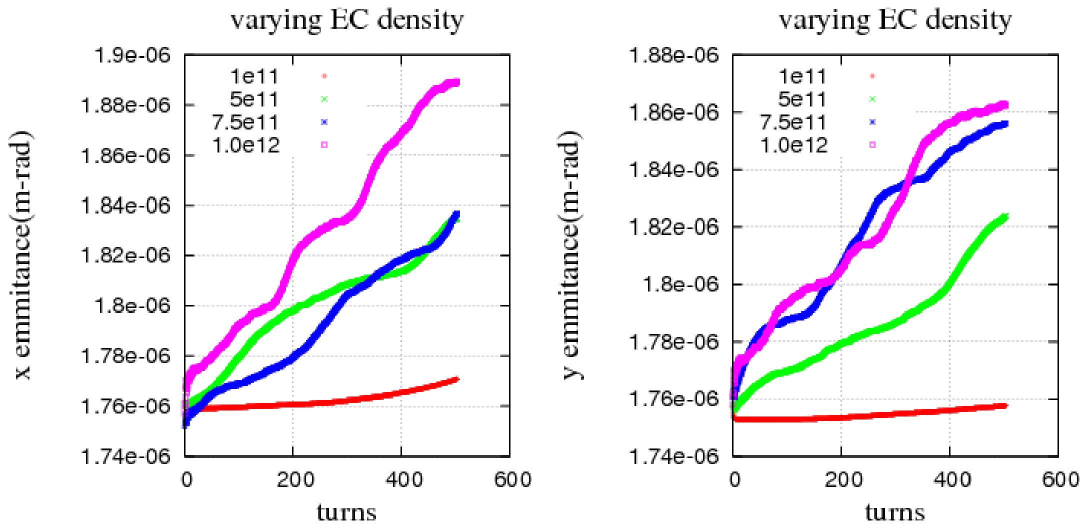

Figure 2: Evolution of emittance in the absence of synchrotron motion

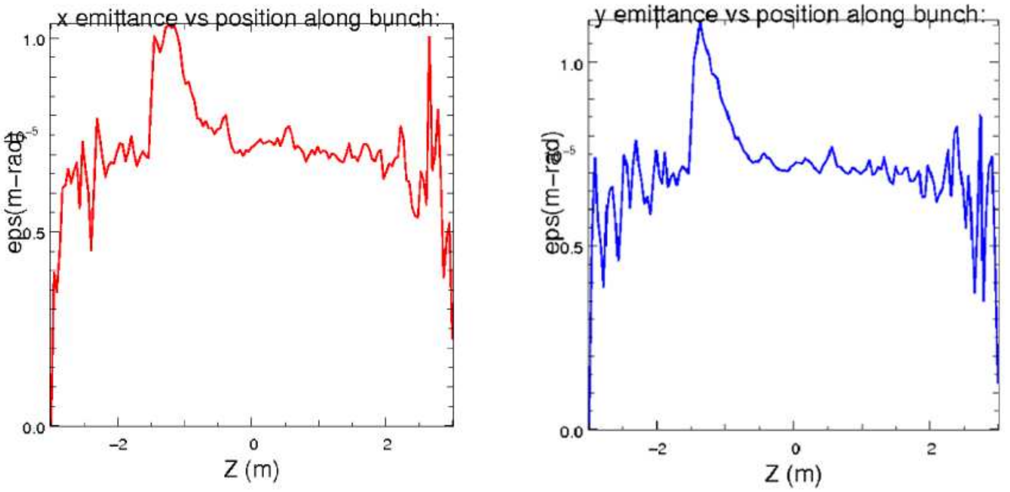

Figure 3: Distribution of emittance along the bunch after 500 turns

Table 1: parameters used for the computations

Circumference	3319.419 m
Vac. chamber size $(x \times y)$	(12.3×4.9) cm
Tunes (x, y, s)	$(26.4249,\ 25.415,\ 0.013)$
Bunch intensity	3×10^{11}
Beam energy	8.9 GeV
No. of bunches	504
Bunch length	0.75 m

study progresses. For the sake of simpilicity and the purpose of obtaining an initial set of results, we use a uniform beta function that is obtained from the tune and the circumference of the ring. All the simulations in this section were done with four stations that were evenly spaced around the ring and at which the beam-electron cloud interaction was calculated, based on the quasistatic model described in the previous section.

Figure 2 shows the evolution of the beam emmittance in the absence of synchotron oscillations for different electron cloud densities for the horizontal and vertical planes respectively. The initial emmitance (rms) was 1.7×10^{-6} m-rad. A uniform beta function was used and was calculated from the tune and circumference of the machine. Thus, the value of β_x was 19.99 m, $\beta_y = 20.786$ m, and the corresponding beam size $\sigma_x = 5.8$ mm and $\sigma_y = 5.94$ mm. The figures show a steady increase in beam emmitance with increased electron density. We may expect the growth to slow down after a sufficiently large number of turns.

Figure 3 shows the emittance distributions along the length of the bunch. The figures show a clear evidence of a head -tail interaction. As the beam enters the cloud re-

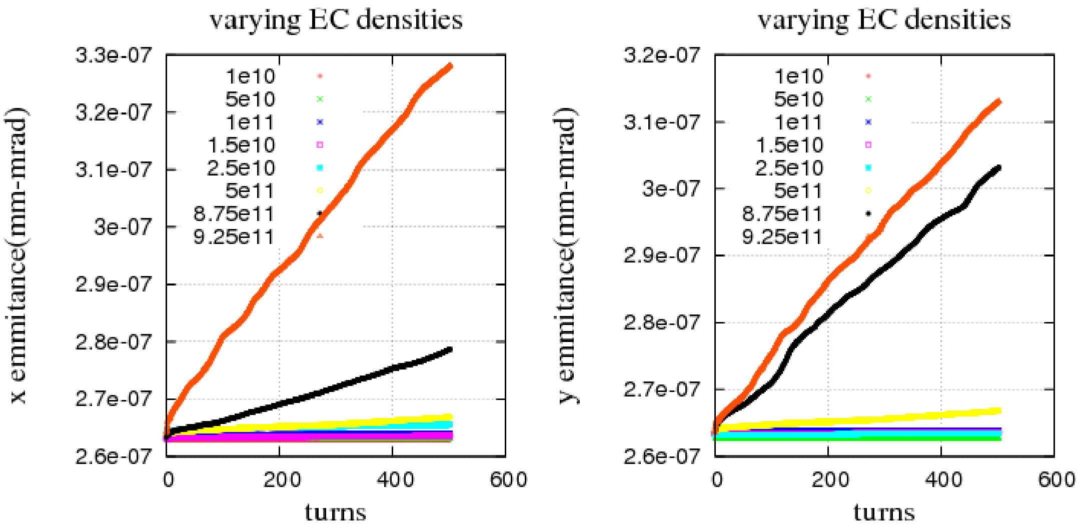

Figure 4: Evolution of emittance in the presence of synchrotron motion

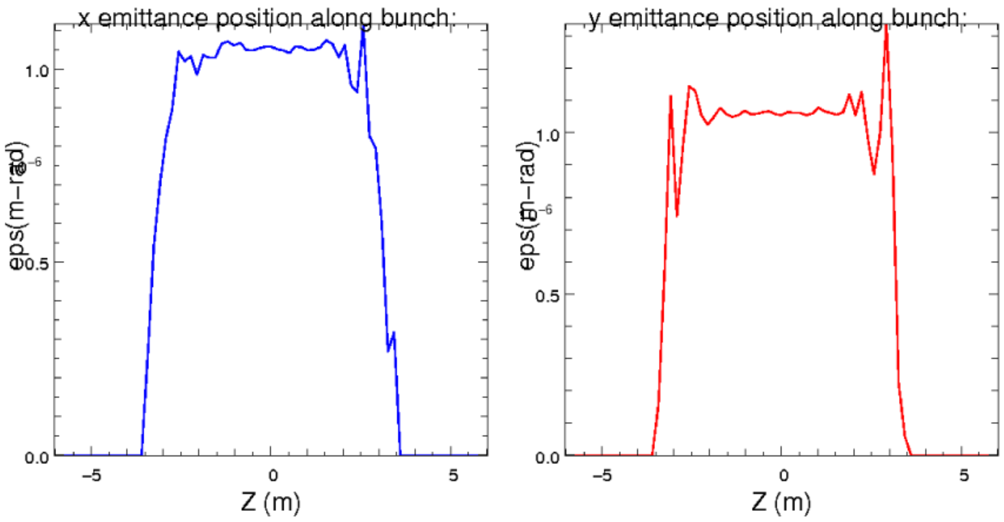

Figure 5: Distribution of emittance along the bunch after 500 turns

gion, the cloud experiences a pinching effect due to which, the space charge force from the electrons becomes more intense when the tail section of the bunch encounters the electron cloud. We clearly see such an effect in Fig. 3. Although, it is an unrealistic scenario in which synchotron oscillations have been disregarded, the results are still useful in showing the existence of a head-tail interaction. In the presence of synchrotron oscillations, the distribution becomes more even, which does not imply that such an interaction has been eliminated.

Figure 4 shows the evolution of transverse emittance in the presence of synchrotron oscillations. The initial rms beam emittance was 0.263×10^{-6} m-rad, which coresponds to a beam size of $\sigma_x = 2.29$ mm and $\sigma_y = 2.33$ mm. These calculations were done for a wide range of electron densities and we see the existence of a threshold electron density at around 5×10^{11} m^{-3} beyond which a rapid growth in emittance was observed. The initial energy spread and bunch length were made to match so that there was no significant oscillation in the bunch length.

Figure 5 shows the emittance distribution along the bunch corresponding to an electron density of 1×10^5 m^{-3}. We notice that the emittance distribution becomes more even when compared to the case given in Fig. 3. The distribution was plotted after 500 turns which corresponds to about 5 synchotron periods.

THE EFFECT OF VARYING THE NUMBER OF STATIONS

In the previous section, we showed results of computations in which, for all cases, we used 4 stations that were

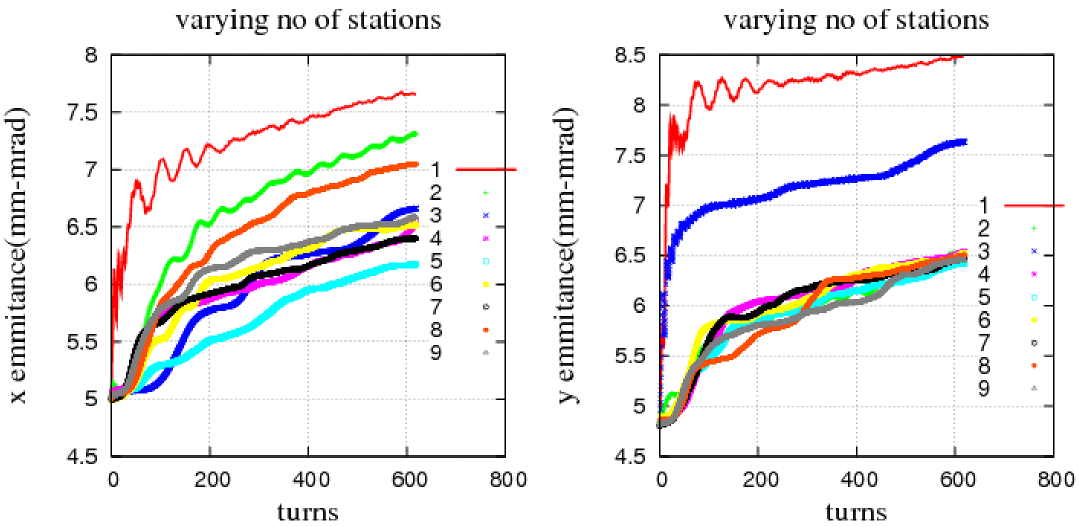

Figure 6: Evolution of emittance for different number of stations

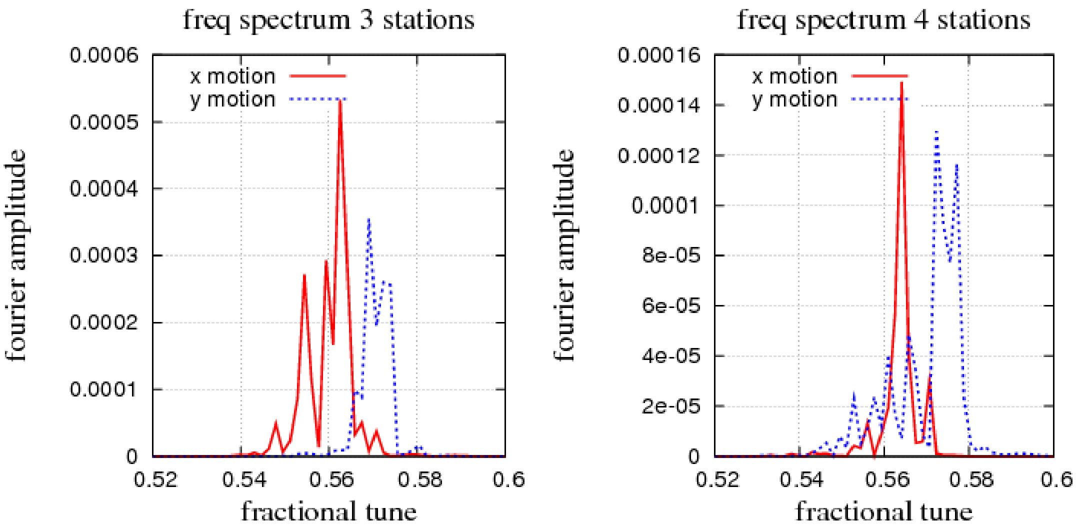

Figure 7: Frequency spectrum of beam centroid for 3 and 4 stations

evenly distributed around the ring. In this section we discuss the effect of varying the number of stations. This has already been studied using HEADTAIL for a different set of parameters [6].

Figure 6 shows the emittance evolution for different number of stations. The electron cloud density was 1×10^{12} m^{-3} in all cases and synchrotron motion was absent. The figures clearly show that there is no trend in the behaviour of emmitance evolution with increase in the number of stations. We see a larger emmitance growth rate for one station and beyond that the rate does not converge toward a single value with increasing number of stations. This form of behaviour may be attributed to nonlinear coupling between the x and y planes from the electron cloud, in which the nature of the coupling is variable with number of stations.

Figure 7 shows the Fourier spectrum of the motion in the horizontal and vertical planes for 3 and 4 stations. We see that the spectra are very different although the number of stations are adjacent to each other. The variation in the nature of the nonlinear coupling for the two case is because the phase advance at which the electron cloud - beam interaction takes place varies greatly at two adjacent number of stations. Thus one may expect that such a variation becomes less rapid when the number of stations approaches the tune of the machine. We expect that with sufficiently large number of stations, we will see that the emittance growth rate will converge toward a definite value and along with that so will the Fourier spectra.

SUMMARY

In this paper, we have shown an existence of a threshold for fast emittance growth beyond an electron cloud density of $5 \times 10^{11} m^{-3}$ for a simplified model represnting the Fermilab MI. The beam parameters corresponded to that at injection representing the conditions for the HINS. Our goal in this effort is to perform a more detailed analysis in order to understand the influence of the electron cloud over the beam for the MI with conditions that would more closely represent that of the the HINS.

A brief description of the quasistatic model is provided, which has been successfully implemented into the particle-in-cell code WARP. Calculations were performed with and without synchrotron motion. The calulations performed without synchrotron oscillations were useful in detecting the presence of a head-tail interaction. In all our calculations, we used a uniform beta funtion with four stations for electron cloud-beam interactions that were evenly distributed over the ring.

We showed that increasing the number of stations does not necessarily result in a convergence in the emittance growth rate to a single value. We stated that this was a result of nonlinear coupling between the x and y planes due to the electron cloud-beam interaction. Since the phase advance at which this interaction takes place greatly varies for adjecent values of station numbers, we expect that the dynamics resulting from the coupling will also vary. This was verified by examining the Fourier spectra for 3 and 4 stations respectively. We expect that one will reach a convergence as the number of stations is of the order of the tune of the machine. However, even with a small number of stations, we do see that the emittance variation with number of stations is within a reasonable limit and does not lead to stable and unstable motion between adjacent values of station numbers. Thus, for an initial analysis, involving a rough estimate of a threshold electron density for fast emittance growth, using 4 stations can be justified. Using a much larger number number of stations will become necessary when an accurate estimate of emittance growth needs to be performed.

We are in the process of increasing the complexity of the system in our simulations in order to better represent the conditions of the accelerator. In order to increase the number of stations, it would be essential to perform computations on multiple processors and use adaptive mesh refinement. WARP is equiped with both the capabilities. Along with a sufficiently large number of stations, it would be feasable to include a nonuniform beta function distribution. It would be interesting to study the effects of dispersion, chromaticity and space charge, which is a straightforward extension of the current model. We also intend to study multibunch effects within the quasistatic model.

In this paper we have reported results of work still in progress. So far the results clearly indicate that electron cloud effects are important for the HINS project and a more exhaustive study needs to be conducted.

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