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SIMULATIONS OF ELECTRON CLOUD EFFECTS ON THE BEAM DYNAMICS FOR THE FNAL MAIN INJECTOR UPGRADE *

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Abstract

The Fermilab main injector (MI) is being considered for an upgrade as part of the high intensity neutrino source (HINS) effort. This upgrade will involve a significant increasing of the bunch intensity relative to its present value. Such an increase will place the MI in a regime in which electron-cloud effects are expected to become important. We have used the electrostatic particle-in-cell code WARP, recently augmented with new modeling capabilities and simulation techniques, to study the dynamics of beam-electron cloud interaction. This work in progress involves a systematic assessment of beam instabilities due to the presence of electron clouds.

INTRODUCTION

The Main Injector (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 (HINS). Electron clouds are expected to play an important role in this application in determining parameters to optimize the performance of the HINS. In this paper, we present results corresponding to the injection parameters only. A list of accelerator parameters representing the MI is given in table 1. The machine undergoes transition during the energy ramp.

Table 1: Parameters Representing the MI

circumference	3319.419m
x tune	26.4249 (x)
x tune	25.415 (y)
injection energy	8.9 GeV
top energy	120 GeV
bunch intensity	3 $\times 10^{11}$
injection bunch length	0.75m
initial emittance (transverse rms x,y)	0.263 mm-mrad
transition gamma	21.6
harmonic number	588
vac. chamber size (elliptic)	4.9cm (x), 12.3cm (y)

ASSESSING A THRESHOLD ELECTRON DENSITY FOR FAST EMITTANCE GROWTH

The "quasistatic" method has been implemented into the particle-in-cell code WARP [1, 2]. In this method, the electron cloud occurring over a certain segment of the storage ring is collapsed into a two dimensional charge distribution while the beam is divided into several slices. The two dimensional electron cloud is distributed over different points of the ring referred to here as stations. The beam and electrons are made to interact at every station and after the interaction, the particles are moved using a transfer map between stations. This algorithm has been implemented in other codes such as HEADTAIL [3] and QUICKPIC [4]. A more comprehensive list of codes implementing similar methods may be found in Ref [5].

In the current model, we choose four stations equally spaced around the ring where the electron cloud-beam interaction takes place. A uniform beta function was used, which was calculated from the tune and the circumference of the accelerator. This gives us $\beta_x = 19.99m$ and $\beta_y = 20.786m$. A fifth station with no electron cloud provides an RF kick. In this calculation, we "store" the beam at injection energy and compute the evolution of the bunch for 500 turns. The initial energy spread and bunch length was made to match so there was no significant oscillation in the bunch length. For the sake of simplicity, we use a chamber with circular cross section.

In Fig 1 we plot the evolution of the emittance growth. The beam size obtained from the initial emittance and beta functions were $\sigma_x = 5.8mm$ and $\sigma_y = 5.94mm$. The calculation was done for a wide range of electron densities and we see the existence of a threshold electron density at around $5 \times 10^{11} m^{-3}$ beyond which a rapid growth in emittance was observed.

Table 2: Computational Parameters

no of beam slices	140
transverse grid cells	128×128
no. of beam particles	300000
no. of electrons	100000
chamber radius	2.45cm

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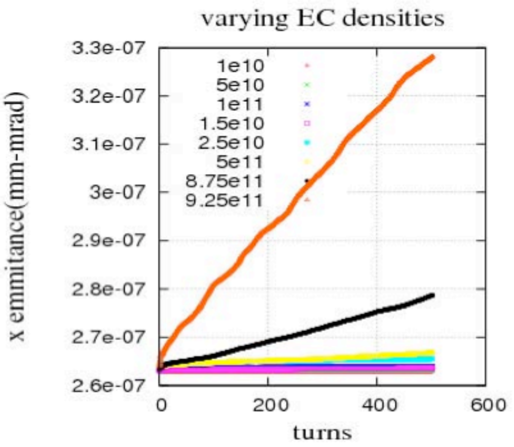

Figure 1: Evolution of x emittance for different electron densities.

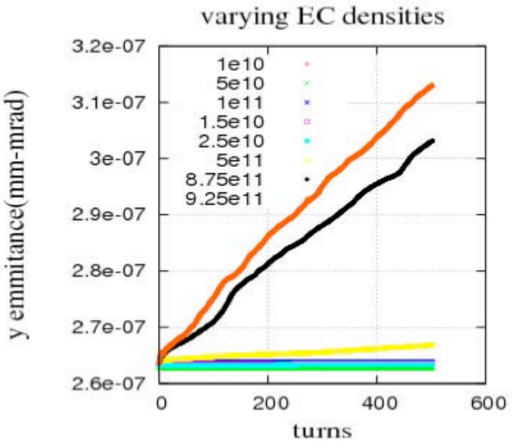

Figure 2: Evolution of x emittance for different electron densities.

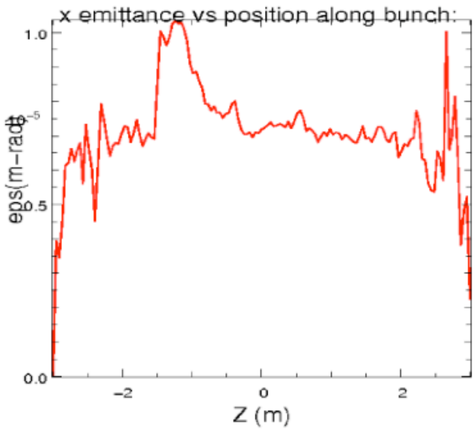

Figure 3: Distribution of emittance along bunch in the absence of synchrotron oscillation, after 500 turns.

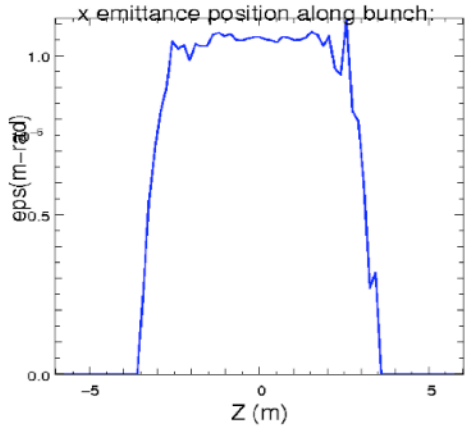

Figure 4: Distribution of emittance along bunch in the with synchrotron oscillation, after 500 turns.

EMITTANCE DISTRIBUTION ALONG THE BUNCH

The electron 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. It is clear that synchrotron oscillations, which lead to a periodic interchange between the head and tail will play a strong influence over such an interaction.

We observe the transverse emittance along the bunch to study the behavior of the head-tail interaction. We compute this for (a) a beam with no synchrotron oscillation and (b) beam with synchrotron oscillations. In the first case, in order to prevent a drift in the longitudinal direction, we set the energy spread to zero. Although we show only the horizontal emittance in this paper, we state that the behavior in the vertical plane is very similar. The electron densities used were 5×10^{11} for both cases.

Figure 3 shows the emittance distribution along the bunch for the case where synchrotron motion is absent. In this case the particles in the tail region, which experience the maximum electron space charge force, create a spike in the emittance distribution. One would expect this spike to move toward the center with increase in electron density, and beyond a point the motion would become unstable.

Figure 4 shows the emittance in the presence of synchrotron motion. In this case, the growth at the tail is seen to even out due to the longitudinal oscillation of the particles and the periodic interchange between the head and tail. The simulation was carried out for over about 5 synchrotron periods (500 turns), which corresponds to about 10 interchanges between head and tail.

Thus, although the absence of synchrotron motion is unrealistic, studying such a case provides an illustration of the dynamics of the electron cloud - beam interaction. The interaction between the electron cloud and beam creates a different tune shift at different points along the bunch, with the tune shift increasing as one approaches the tail, causing an increased emittance growth in that region. It would be interesting to study the variation of tune shift along the length of the bunch and how this correlates with synchrotron motion.

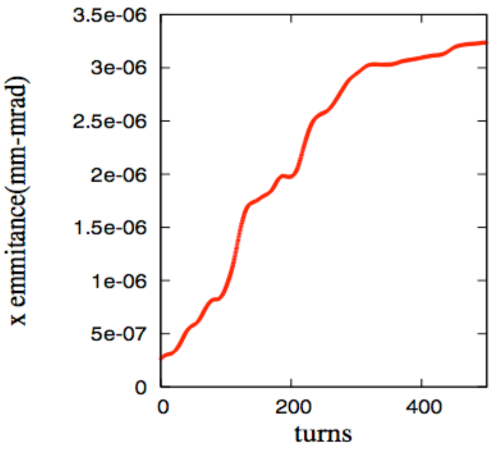

Figure 5: Distribution of emittance along bunch in the with synchrotron oscillation, after 500 turns.

STUDYING AN EXTREME CASE

In order to better understand the consequences of the head-tail interaction, we study a case where the electron density was raised to 7.5×10^{12} which is an order of magnitude above the threshold electron density. While this is much higher than the electron densities that exist in accelerators, it gives us a better idea of the process of emittance growth due to the electron cloud - beam interaction.

Figure 5 shows the rate of emittance growth, which is very rapid initially, until it slows down at a later stage. Figure 6 shows the resulting emittance distribution along the bunch. We see that the emittance is spiked up near the vicinity of the head and tail. This happens because the characteristic time over which the emittance growth occurs in the tail region is comparable to the synchrotron oscillation period. The process may be understood as follows. It was mentioned in the previous section that the tail region undergoes a larger tune shift. If this is large enough to create a considerable emittance growth difference within a synchrotron period, then the growth begins to pile up in the head/tail region before the synchrotron motion has a chance to even out the emittance distribution along the bunch.

SUMMARY

In this paper, we have shown the existence of a threshold for fast emittance growth beyond an electron cloud density of $5 \times 10^{11} m^{-3}$ for a simplified model representing the Fermilab MI for proposed HINS upgrade parameters. The existence of the threshold may be attributed to a coupling between the head-tail interaction and the synchrotron motion. 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. Some notable features that will be seen in future results would be the inclusion of dispersion, chromaticity and space charge effects of the beam. We have also developed the ability to input a table of twiss parameters into the code rather than use a constant focusing model. This would result in a closer representation of the lattice of the machine. Using a larger number of stations would also provide a better estimate of emittance growth rate. It has been shown that the emittance growth has some uncertainty associated with the number of stations used [6, 2], which has been attributed to a nonlinear coupling in the transverse motion resulting from the electron cloud - beam interaction and the phase advance at which the corresponding station is located. This uncertainty is expected to be eliminated when the number of stations approaches the tune of the machine.

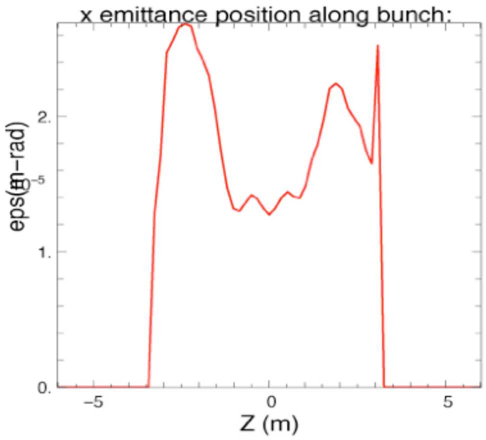

Figure 6: Distribution of emittance along bunch in the absence of synchrotron oscillation, after 500 turns.

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