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A preliminary report on electron cloud effects on beam dynamics for the FNAL main injector upgrade

Kiran G. Sonnad, Miguel A. Furman and Jean-Luc Vay
Center for Beam Physics
Lawrence Berkeley National Laboratory, Berkeley, CA 94720
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The code WARP-POSINSTS has been recently modified in order to simulate synchrotron oscillations as well as the effect of dispersion in the ring. In addition to this, the code now has the ability to accommodate real lattice parameters of the the ring as opposed to the continuous focusing or uniform beta function model that has been used up to now. In this report we discuss the utility of these features. In the current document, preliminary results of beam propagation in the absence of synchrotron motion are presented. We have proposed to examine the results obtained using the additional features only after the code has been benchmarked against previously obtained results from a different code. We also discuss the importance of simulations for studying the propagation of microwaves through electron clouds. The electromagnetic particle-in-cell code VORPAL has been setup for performing these simulations and we present our first set of results here.

I. INTRODUCTION

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 present set of features that have been developed into WARP are based on the scheme already implemented into the codes HEADTAIL [1] developed at CERN, and QUICKPIC [2] 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 distributions of the two species are evolved accordingly. 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 valid for the motion of a single particle. Thus, the single particle transfer map is concatenated with the series of “kicks” along the length of the bunch occurring due to the presence of the electron cloud. The maps may be made to include synchrotron oscillations as well as dispersion. Results from this code have been benchmarked against that obtained by the code HEADTAIL for parameters representing that of LHC for the case where synchrotron oscillations are not included [3]. A schematic of the simulation model is shown in Fig. 1.

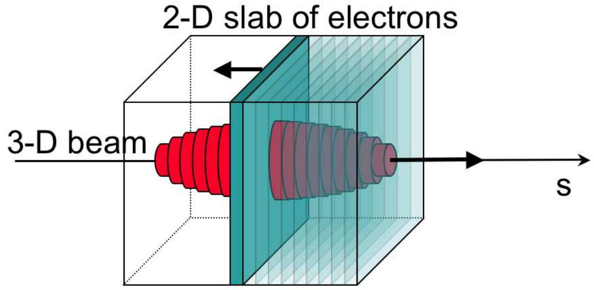

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FIG. 1: A schematic of the modeling scheme used in the current simulation results

II. DISCUSSION ON SIMULATIONS FROM WARP

In this report we present results for the FNAL main injector (MI). The simulation results with synchrotron oscillations need further examination and also need to be verified against results obtained from HEADTAIL. For this reason we report only the effects in the case where longitudinal forces are absent.

The growth of emittance is plotted in order to get an overall estimate of the degradation of the beam quality due to the presence of electron clouds. The emittance distribution and the transverse centroid position along the bunch is observed in order to examine the possibility of a head-tail interaction. In the present set of results, we have used four stations all with the same beta function. Two values of electron cloud densities were used. All the simulation parameters are given in table I

Figure 2 and 3 show the initial growth in emittance in the x and y plane respectively. The growth is higher for the case of electron density of $10^{12} m^{-3}$. The rate of emmitance growth is expected to decrease with turns as it approaches an equilibrium in both cases. Figures 4 and 5 show the variation of the transverse emittances along the bunch. Here, we notice that there is a significant

TABLE I: Table specifying input parameters of WARP simulations

Number of protons per bunch	3×10^{11}
Electron cloud density	$1 \times 10^{12} m^{-3}, 1 \times 10^{11} m^{-3}$
Number of macro particles, protons	100000
Number of macro particles, electrons	300000
Number of slices for bunch	140
Number of cells in mesh	128 × 128
Initial x and y rms emittance	$0.26 mm - mr$
Beam energy	8.9GeV
Horizontal tune	26.424996
Vertical tune	25.415003
uniform beta x	19.992 m
Uniform beta y	20.7868 m
Radius of chamber (currently assumed circular)	2.45 cm

growth in emittance in the tail area in both the cases.

The mean transverse positions along the bunch are plotted in Figs. 6 and 7. It may be noted that there is strong variation in the transverse position at the tail of the bunch. This, along with the longitudinal emittance distribution suggest that there is a transfer of energy between the head and tail of the bunch as a result of the wake created by the leading bunch slices. It will be interesting to study this head-tail interaction in the presence of synchrotron oscillations where their respective roles are periodically interchanged. It is also important to repeat these studies with a greater number of stations. Greater number of stations leads to dilution of the intensity of electron cloud per station and this could have an effect on the nature of the head tail interaction. Despite the preliminary nature of the results, there is clear indication that electron cloud effects on the beam are significant and more detailed studies are required.

III. PROGRESS ON ADDING NEW SIMULATION PROCEDURES

It has been shown by us in a previous report that the emittance growth pattern does not have a regular behavior with increasing number of stations, at least up to 9 stations. This result is consistent with that obtained by HEADTAIL for the LHC. It has been suggested that a monotonic behavior with increase in stations can be reached only when the number of stations is greater than the betatron tune [4]. This enables one to resolve the betatron oscillations, and consequently electron clouds will now provide "kicks" at phases that are sufficiently spread out in order to avoid any possible resonances arising from the model. We propose to perform more calculations with a greater number of stations. In addition to using increased number of stations, we have already included the possibility of specifying a discrete set of lattice parameters at each station. These include local parameters such as (1)beta functions, (2)alpha functions, (3)dispersion, (4)phase advance, (5)position of each station along the rind. and global parameters which are betatron tunes, synchrotron tune, slippage factor, ring circumference etc. Using these parameters, the code computes linear transfer matrices in six dimensional phase space. Coupled with these stations, one may provide one or more RF kicks in each turn. The maps obtained by the code have been examined for some simple cases. Runs will be performed after the code has been verified against HEADTAIL with the case where synchrotron oscillations are included. A particular advantage of varying the beta function along the ring is that it introduces variation in the transverse beam size which in turns leads to variation in the nature of interaction with the electron cloud.

The procedure to include chromaticity and self field effects of the beam is straightforward in the current setup. It may be noted that these are nonlinear effects and in order to fully understand the nonlinear contribution coming from the electron clouds, it is important to retain all other transport sources between stations to be linear. We propose to examine these additional effects as a next stage in our study. It would also be interesting to vary the beam energy in order to replicate the energy ramp in the simulation. However, this will have to done in two stages because the linear transport map formulation is not valid when the beam is very close to transition. Thus, it would be suitable to study the dynamics near transition as a separate problem.

IV. FIRST RESULTS OF SIMULATION OF MICROWAVE PROPAGATION

We have started performing simulations to study the physics of microwave propagation through an electron cloud in a beam pipe. After some theoretical analysis of the problem and an examination of the results obtained by Kroyer and Caspers [5], it was clear that an electromagnetic particle-in-cell simulation tool is required for a thorough analysis of the problem. This is because the system becomes very complicated in the presence of a dipole magnetic field and when a periodic passage of a beam is included. Moreover, analytic models generally treat the system to be perturbed from an equilibrium distribution, which need not be the case in this situation. We are in the process of to setting up simulations using the electromagnetic particle-in-cell code VORPAL [6] for this.

The simulation results shown here are for a rectangular cross section chamber with a uniform electron distribution in position space. A TE mode wave guide is propagated across the beam pipe in a field free region. A summary of the simulation parameters are given in table II.

Figure 8 shows the nonzero transverse component of the electric field just after the wave is launched and after the end of the run. One can clearly notice the distortion

TABLE II: Table specifying input parameters of VORPAL simulations

waveguide length	0.5m
waveguide crossection	$7.5cm.5cm$
number of grid cells	$32 \times 16 \times 16$
electron density	$1 \times 10^{12} m^{-3}$
number of macro particles (one particle per grid cell)	8192
microwave frequency	3GHz
cutoff frequency	2 GHz
physical time simulated	$70 \times 10^{-9} s$
power of input microwave	1×10^{-3} watts

in the electric field produce by the electrons. We need to implement more diagnostic procedures in order to examine properties such as phase shift, frequency spectrum etc. of the output wave.

In the future, we propose to examine the effect of a dipole and solenoidal magnetic fields and also simulate the periodic passage of a proton bunch. Besides performimg calculations for the FNAL MI parameters, it would be interesting to compare these results with the experimental results of T. Kroyer and F. Capers (which involves a dipole magnet) and also the proposed experiment at the PEP-II LER (which will involve a solenoidal magnet).

V. CONCLUSION

Simulations from WARP indicate the presence of a head-tail interaction, leading to a significant emittance growth. This emittance growth is greater for a higher electron cloud density. This phenomenon in observed for the simple case of only four stations of beam-electron-cloud interactions, all with the same beta function and in the absence of synchrotron oscillations. Our preliminary results indicate that electron cloud effects are significant and it is necessary to study these effects with more realistic models. The code has been further developed to model synchrotron oscillations. This is yet to be benchmarked against the code HEADTAIL. In addition, WARP now has the ability to use a nonuniform beta function distribution along with other effects such as dispersion. Simulations with these additional features will be performed in the near future.

We have acquired a simulation tool to model the microwave transmission through electron clouds. Simulations using the code VORPAL will be performed that will represent the conditions at PEP-II LER, CERN SPS and the FNAL MI. Diagnotic tools will be implemented in the simulation so that we can record experimentally measurable quantities such a phase shift and the frequency spectrum of the out-coming microwave radiation.

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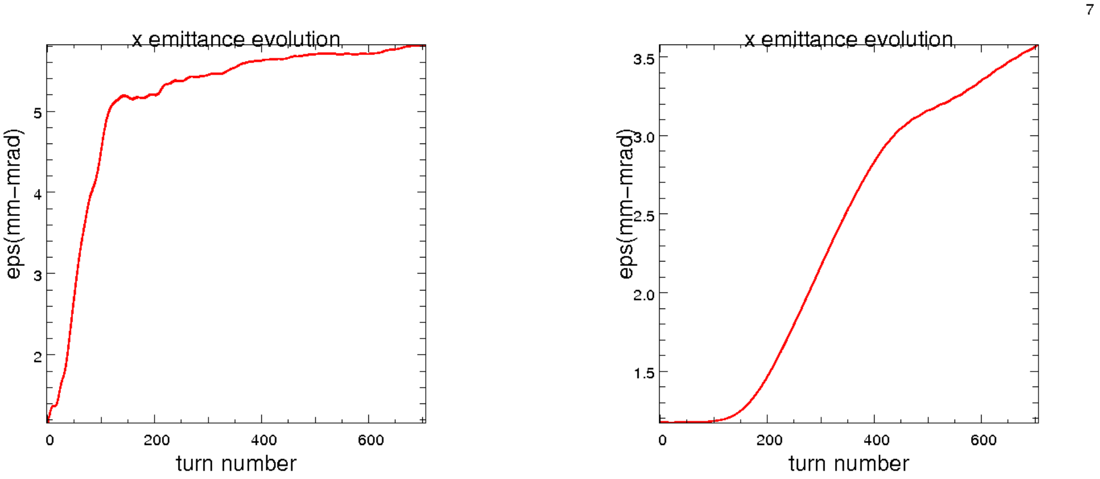

FIG. 2: x emittance growth with turn for electron density of $10^{12}m^{-3}$ (left) and $10^{11}m^{-3}$ (right)

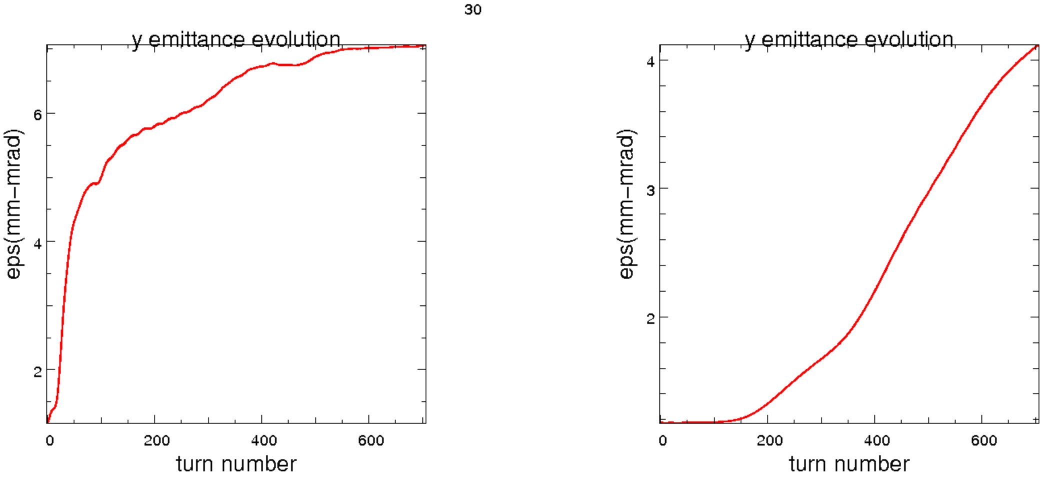

FIG. 3: x emittance growth with turn for electron cloud density of $10^{12}m^{-3}$ (left) and $10^{11}m{-}3$ (right)

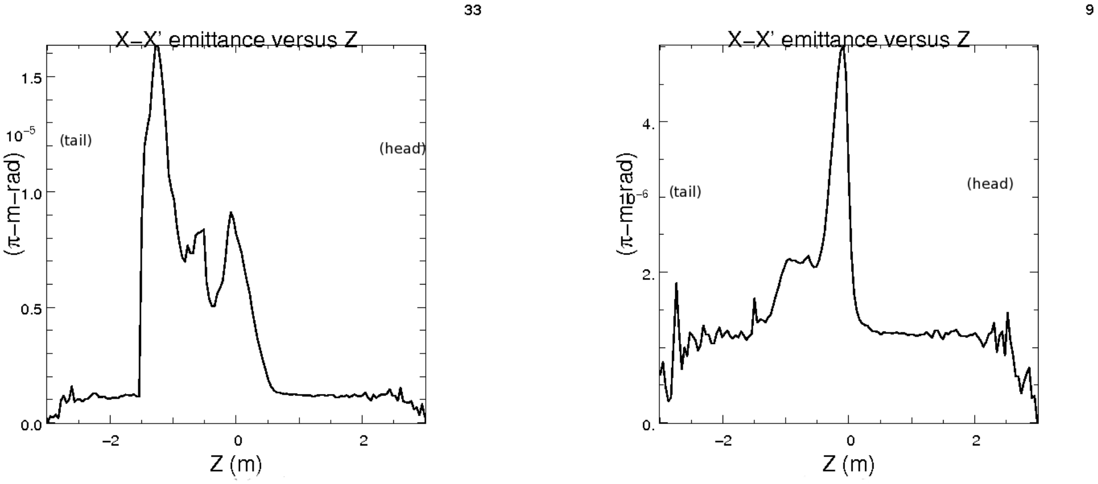

FIG. 4: x emmitance distribution along bunch for electron cloud density of $10^{12} m^{-3}$ (left) and $10^{11} m^{-3}$ (right)

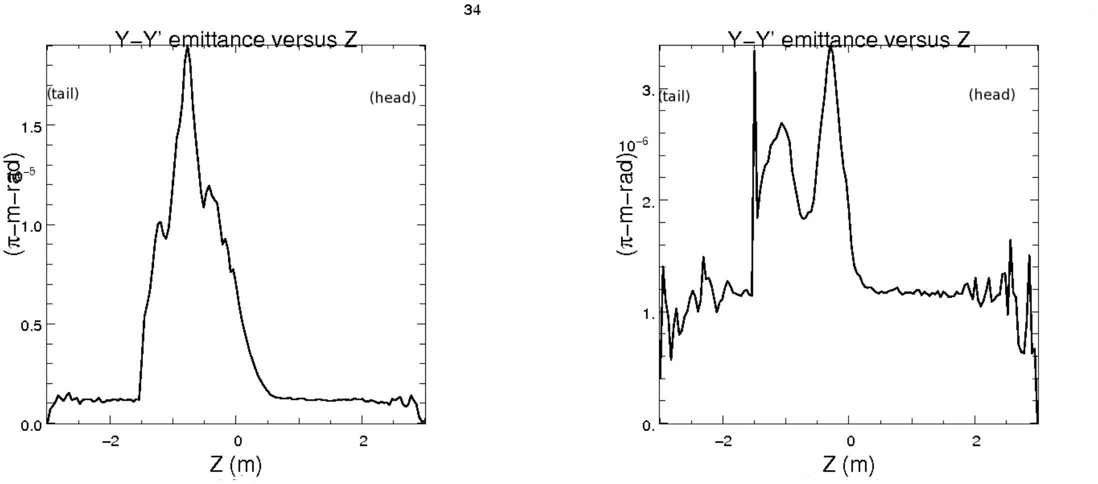

FIG. 5: y emmitance distribution along bunch for electron cloud density of $10^{12} m^{-3}$ (left) and $10^{11} m^{-3}$ (right)

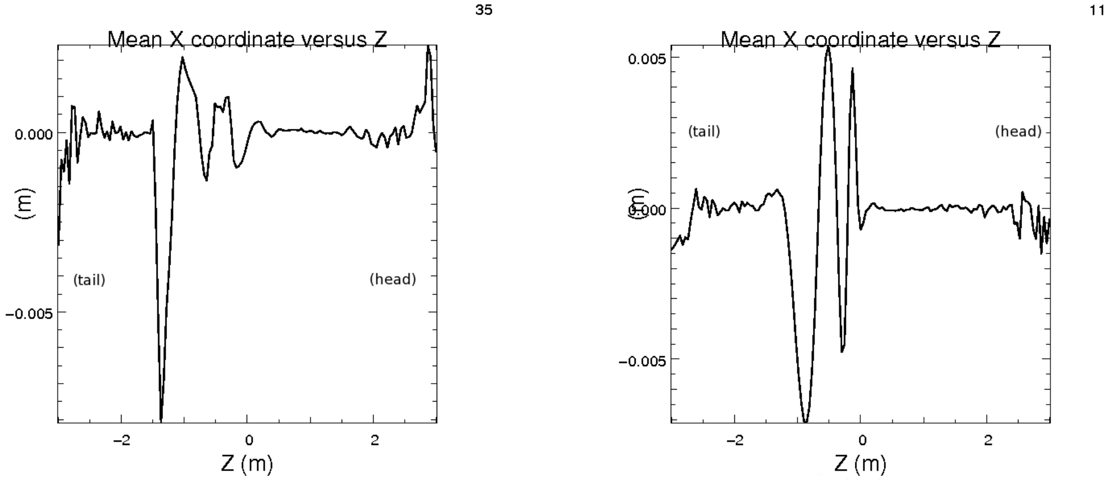

FIG. 6: x position of centroid along bunch for electron cloud density of $10^{12}m^{-3}$ (left) and $10^{11}m^{-3}$ (right)

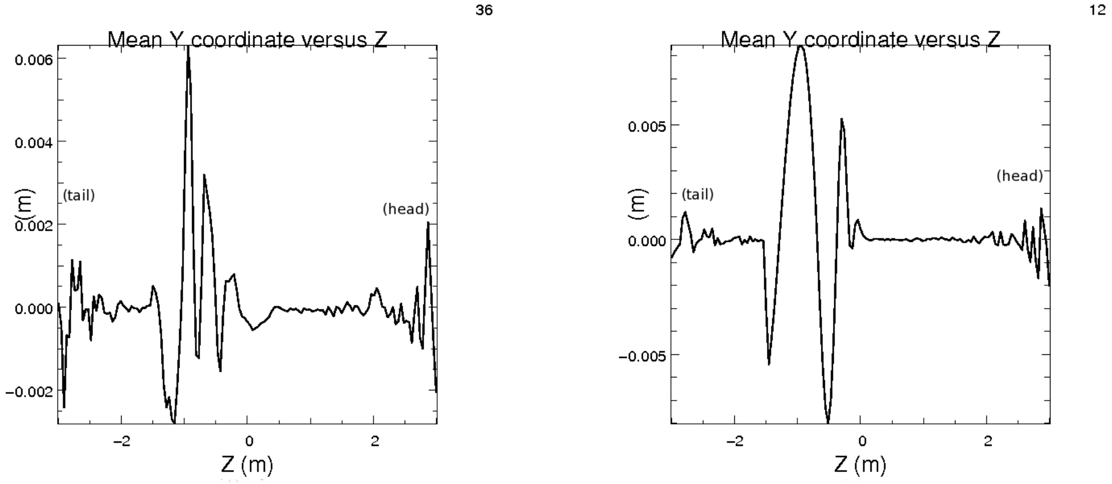

FIG. 7: y position of centroid along bunch for electron cloud density of $10^{12}m^{-3}$ (left) and $10^{11}m^{-3}$ (right)

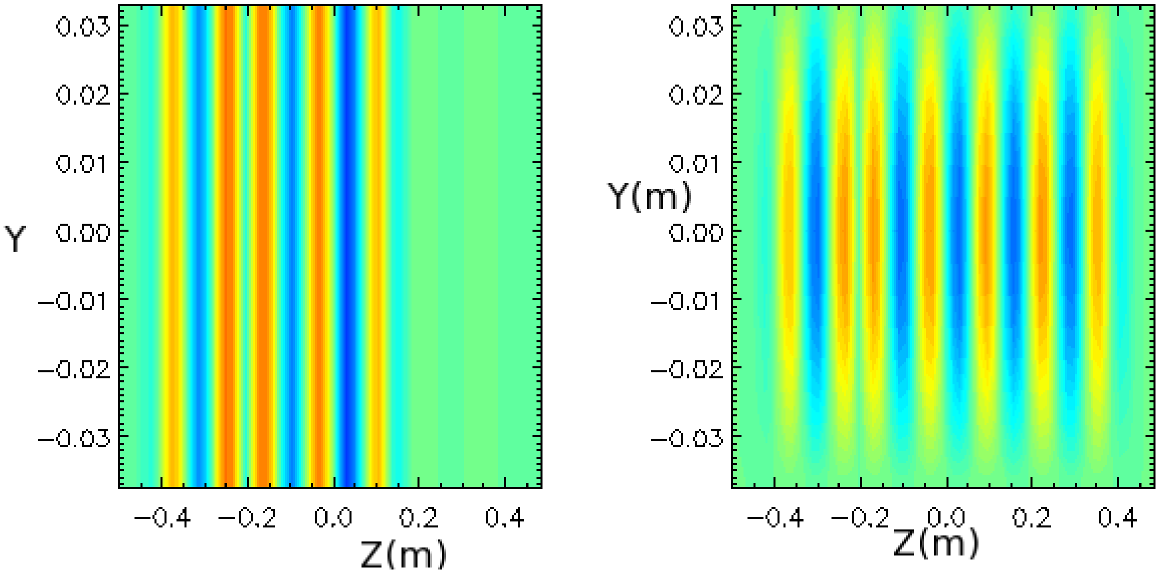

FIG. 8: Transverse (X) component of electric field on YZ plane at (1) t = $1.6 \times 10^{-9} s$ and (2) t = $70 \times 10^{-9} s$.