

Progress on simulation of beam dynamics with electron cloud effects: An update*

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Abstract

This paper provides a brief review of progress on the simulation methods associated with studying the beam response to electron cloud effects. Comparison of results obtained from the program CMAD and other similar programs are reported. An update on recent developments and future planned upgrades to CMAD are discussed.

INTRODUCTION

Studying the influence of electron clouds on the dynamics of beams in storage rings has made steady progress in the last few years. Earlier methods involved using a constant focusing model with interacting points (IPs) at discrete locations around the ring. This was followed by modifying the transport mechanism to that of a simple FODO lattice in a ring with the strengths of the quadrupole magnets adjusted so that the betatron tunes of the model matched with the actual tunes. The latter model helps include several features not to be found in the former one. More recently, considerable progress had been made toward using the full lattice rather than an idealized one. The programs used to produce the results in this paper, namely HEADTAIL [1], WARP [2], and CMAD [3], are capable of all the simulation methods mentioned above.

Dedicated experiments are being performed on a regular basis at CEsrTA to study the interaction between positron beams and electron clouds over a wide range of parameters [4]. These experiments are not only helping us understand the physics of electron effects, but also providing information on the extent of detail that needs to be introduced in order to reproduce the observed effects in the simulation. We have been regularly performing simulations using CMAD in our efforts to validate them with observations being made at CEsrTA. The outcome of this effort will prove very valuable when studying future accelerators such as the ILC and CLIC damping rings, the super B factories and the upgrade of hadron machines such as the Fermilab MI, LHC and SPS.

The general method of performing these simulations involves tracking a certain number of beam particles around the ring with the help of transfer maps, and including electron cloud effects at discrete "interacting points" (IPs) in

the ring. The electron cloud is represented on a two dimensional grid and the beam represents a finite number of 2D grids referred to as slices. The beam is made to pass through the cloud slice by slice and both the electrons and beam particles are evolved dynamically with every cloud-beam slice interaction. This procedure is repeated at every IP. The electron cloud distribution gets refreshed after every interaction but the beam distribution evolves throughout the process. One also has the option of using a "frozen field" approximation where the electric field produced by the electron can be reused for a given time period before refreshing it again with a Poisson solver. The beam is usually tracked for several turns, the number depending upon the characteristic time scale of the phenomenon to be understood. For example, simulating head-tail interaction requires tracking for several synchrotron periods.

Despite the overall features of the simulation methods being fairly common, subtle differences exist in ways the calculations are carried out by different programs. For example, the program, CMAD divides the beam into slices such that the total charge on each slice is the same. Some other programs such as WARP and HEADTAIL divides the beam into slices of equal length. Both methods have their own advantages and disadvantages. Since the different programs have been developed independently by different groups, it is unlikely that a trivial mistake made in one of them would be repeated in another. Thus it very important to validate the results of such programs to (1) eliminate the possibility of a mistake or bug (2) to ensure that none of the subtle differences in calculation methods such as the one mentioned above lead to significant numerical errors.

There has been a continued effort in comparing results from different programs [5, 6] and this paper is meant to provide a summary of the latest on this. Besides comparing results from different programs, we are making an effort to study the effect of numerical noise on emittance growth. Emittance growth has been experimentally observed and very similar dependencies to physical parameters have been seen in simulations for CEsrTA. At the same time, it is well known that particle-in-cell simulations cause numerical noise. The numerical noise could cause a particle confined on a trajectory exhibiting stable motion to artificially wander into a region of unstable motion. To study the possibility of this happening, one needs to compare emittance growth rates over a number of computational parameters. If emittance growth rate varies significantly with

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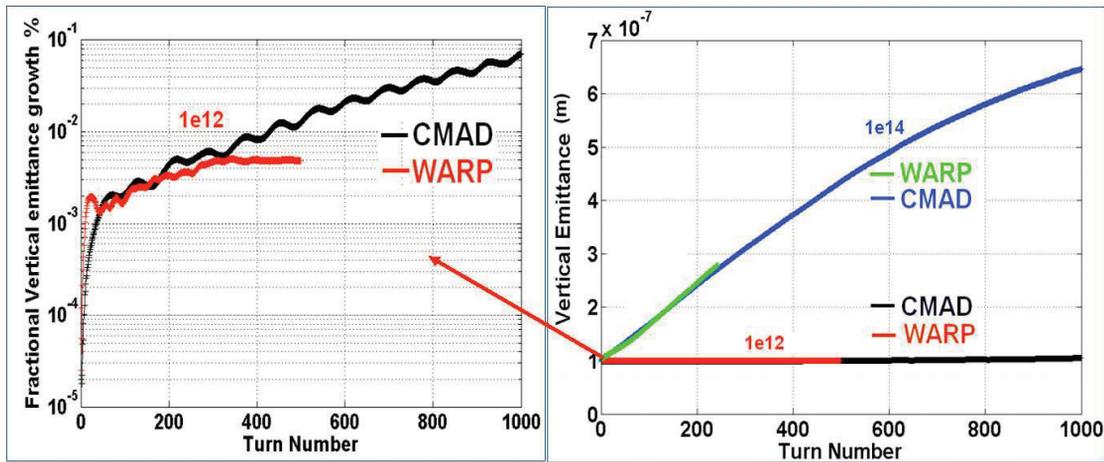


Figure 1: SPS FODO model.

varying number of macroparticles, one can deduce that the result is being dominated by numerical effects. It is important to ensure that such effects are insignificant even if it is not possible to eliminate them.

COMPARISON OF RESULTS FROM DIFFERENT PROGRAMS

Agreement between the programs HeadTail and WARP has been reported for a constant focusing system [6]. Although the parameters used for this study were extreme and not representative of real accelerator conditions, they were well suited for comparison of results from different simulation programs. This is because small inaccuracies are expected to be amplified when conditions such as electron cloud density and chromaticity are exaggerated since both contribute to nonlinearity in the transport system. One case of this study was verified against results obtained from CMAD. This is shown in Fig 2, which was done for parameters corresponding to an LHC type proton beam in the SPS. Emittance growth is tracked for varying electron den-

sities. It may be noticed that the results from CMAD deviate slightly for an electron density of $10^{13}/m^3$ but overall there is reasonable agreement between the three programs.

Another case for benchmarking such results from different programs was initiated by Frank Zimmermann [5] for the SPS, represented by an idealized FODO lattice. This consisted of a FODO structure with thin lens quadrupoles. The strengths of the quadrupoles are adjusted so that the tune of this idealized system matched with the real tunes. Figure 3 gives the twiss functions generated by MADX. Details of all the accelerator parameters of this case can be found in [5] including results obtained using HEADTAIL for the same set of parameters. The comparisons between WARP and CMAD for this case is shown in Fig 1. Unfortunately, at that time we were unable to perform the calculation for a 1000 turns with WARP. Given the available results both the programs show that the emittance growth is very small for the $10^{12}m^{-3}$ electron density case, probably within the extent of contribution from numerical noise. For the $10^{14}m^{-3}$ electron density case however, both programs show a rapid growth in emittance, with very good quantita-

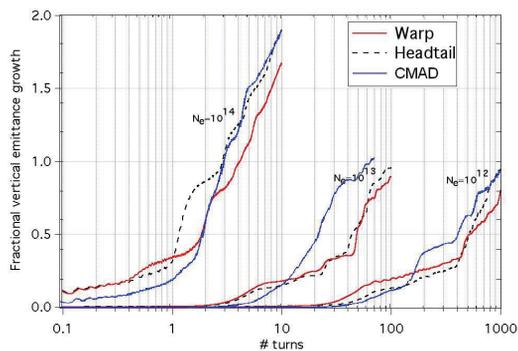


Figure 2: Comparison of results from three simulation programs for a continuous focusing case for an LHC type beam in the SPS.

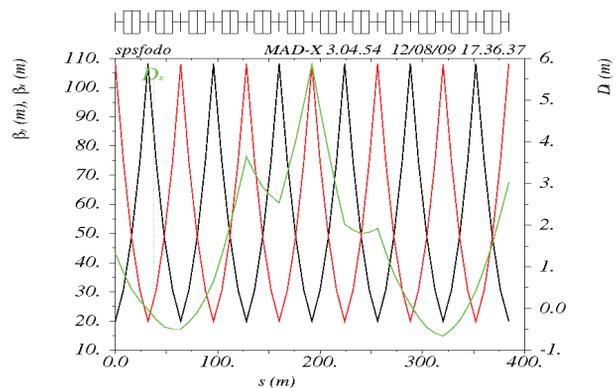


Figure 3: Twiss functions of one FODO cell of the idealized SPS lattice model

tive agreement. The computational parameters used in both the calculations were as follows - The beam was cut into 64 slices, a 64×64 grid was used, 300000 macro protons, and $64^2 = 4096$ macro electrons were used. A "quiet start" (uniform distribution of cold electrons) was considered for the initial electron distribution with 1 electron/cell.

SOME DETAILS ON CMAD

The program CMAD is being actively developed and at the same time being used for simulating electron cloud effects in various machines. This program is capable of parallel simulations which becomes necessary when including the complete lattice for tracking. Calculation pertaining to a specific slice is handled by a separate processor and so ideally the number of processors a job runs on should be equal to the number of slices the beam is divided into, which is typically around a hundred. Inclusion of the complete lattice will take into account variation of the twiss functions around the ring. This is important because the physical size of the beam is influenced by the beta functions and the dispersion, and the response of the electron cloud depends on the physical beam size. The electrons respond to an external magnetic field via the Boris push scheme. Thus in the presence of a dipole field, the electrons move along the field lines with a cyclotron motion, provided the resolution of the grid spacing is within the cyclotron radius.

In the current version of CMAD, the electron cloud is uniformly distributed before the start of an interaction with the beam. We are in the process of improving this so that one could use a more realistic electron distribution as an initial condition. Along with adding features in the simulation program CMAD, we are also developing useful data

output routines that can provide useful information of the dynamics at different levels. Examples include tracking trajectories of individual particles and tracking the transverse displacement of individual slices in order to understand electron cloud induced head-tail motion. A more detailed report of the physics results obtained using CMAD for CEsrTA is given in [7]

Figure 4 shows the trajectories of a particle at two cloud densities. The calculation was done for a CEsrTA 2GeV energy lattice with a positron bunch current of 1mA. The results clearly show that with increasing cloud densities, the motion of the particle becomes increasingly nonlinear. This is more so in the vertical plane where the beam size is much smaller. The vertical emittance was 50pm and the horizontal 2.6nm. The bunch length was 1.2cm.

CONCLUSION

Simulation of electron clouds effects on the dynamics of beams is a very involved procedure. Several assumptions and approximations need to be made and the extent of their validity needs to be carefully studied. The results obtained from independent simulation programs need to be verified against each other to eliminate possible programming errors and to gauge the accuracy of subtle differences in implementation of the same algorithm. This effort of comparison of results needs to be continued and extended to a more detailed set of calculations. We are in the process of comparing analytic estimates of tune shift with CMAD results. Comparisons between CMAD results and those obtained by measurements at CEsrTA are also underway. The eventual goal of this study is to build sufficient confidence so that simulations from these programs can offer guidance in the design of future accelerator facilities and upgrades of existing ones.

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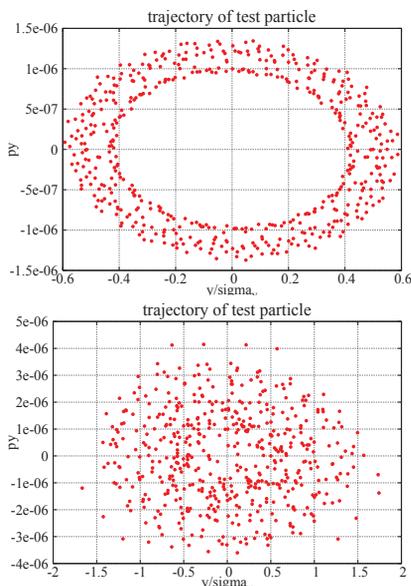


Figure 4: Vertical phase space trajectory of a single positron in a beam with cloud density of $10^{11}/m^3$ and $10^{12}/m^3$ respectively