PARTICLE-IN-CELL CALCULATIONS OF THE ELECTRON CLOUD IN THE ILC POSITRON DAMPING RING WIGGLERS *

C.M. Celata, M.A. Furman, J.-L. Vay, Lawrence Berkeley National Laboratory, Berkeley, CA, U.S.A.
D.P. Grote, Lawrence Livermore National Laboratory, Livermore, CA, U.S.A

Abstract

The self-consistent code suite WARP-POSINST is being used to study electron cloud effects in the ILC positron damping ring wiggler. WARP is a parallelized, 3D particle-in-cell code which is fully self-consistent for all species. The POSINST models for the production of photoelectrons and secondary electrons are used to calculate electron creation. Mesh refinement and a moving reference frame for the calculation will be used to reduce the computer time needed by several orders of magnitude. We present preliminary results for cloud buildup showing 3D electron effects at the nulls of the vertical wiggler field. First results from a benchmark of WARP-POSINST vs. POSINST are also discussed.

INTRODUCTION

The electron cloud in the positron damping ring of the International Linear Collider (ILC) presents such a severe design constraint that until recently it was thought that two positron damping rings would be required, in order to increase the bunch spacing and therefore decrease the electron cloud. It is now hoped that reduction of the cloud by surface coatings of the vacuum pipe, clearing electrodes, or geometric changes to the vacuum chamber such as grooves in the surface will be sufficient to allow a single ring of 6.7 kilometer circumference. Because of the significant influence of the electron cloud on the damping ring design, it is important to calculate its effects as accurately as possible.

The most intense electron cloud is expected to occur in the dipole and wiggler sections of the damping ring, due to photoelectron production by copious synchrotron radiation. Dynamics in the wiggler are inherently three-dimensional, due to the wiggler field. We have therefore begun a study of electron cloud effects in the wiggler using the 3D, self-consistent particle-in-cell code suite WARP-POSINST [1]. In this paper we describe the code and its applicability to this problem. We then discuss the challenges of the ILC wiggler electron cloud calculation, and ways that we expect to meet these challenges using new algorithms in WARP-POSINST. And lastly we show preliminary results from the code for the case of cloud buildup for a nondynamical beam, and first results from a benchmark against POSINST.

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

THE WARP-POSINST CODE SUITE

The WARP-POSINST code suite combines the U.S. Heavy Ion Fusion Virtual National Laboratory code WARP [2] with the electron cloud buildup code POSINST [3,4], which contains detailed models of electron production. For this paper, the code was run using WARP to calculate the electromagnetic fields and the particle dynamics. POSINST routines were called to create photo- or secondary electrons. WARP is a parallelized three-dimensional particle-in-cell code, which uses macroparticles for both beam and electrons. Therefore it is fully self-consistent, i.e., both the effect of the beam on the electrons and the forces of the electrons on the beam are computed. Radiation and retardation of the fields are neglected, but inductive effects are calculated to leading order. Conductors are modelled as perfectly conducting—there is no provision at present for non-zero resistivity.

An important capability of WARP is its ability to do mesh refinement—i.e., to increase the spatial resolution in selected areas of the mesh on which the electromagnetic fields are calculated. The ILC beam, because of its high charge density and small transverse dimensions, creates a steep transverse electric field gradient within a few sigma of the beam. Using a uniform mesh to resolve this gradient would make these calculations intractable because of CPU time and memory requirements, so mesh refinement is essential for this problem. Mesh cells in WARP-POSINST may be of different length along different axes. Cells with ratios as high as 200 between the cell dimensions along different axes (e.g., ratio of the length in the x direction to that in the y direction) have been found to result in an accurate calculation of the field.

WARP also contains a "drift-Lorentz" mover [5], which can be used to track the motion of particles in magnetic fields. This mover allows use of a time step several times larger than cyclotron period. The Larmor radius of the orbit and progress of the gyrocenter are accurately calculated, though the particle phase is not. Thus the space charge is calculated correctly without having to use a time step small enough to resolve the cyclotron motion.

Another new capability is the ability to use different time steps for different particles, depending on certain characteristics—present particle acceleration or proximity to a conductor, for instance.

Finally, a new idea recently published by one of the authors [6] is that of simulating in a Lorentz boosted frame. If the calculation is done in a frame moving at relativistic velocity, the accelerator will appear to be

shorter, and transverse velocities will be lower. As will be discussed below, we believe that this technique will very significantly enhance our ability to simulate the effect of the electron cloud on the beam in the ILC.

NUMERICAL CHALLENGES OF THE ELECTRON CLOUD PROBLEM IN THE ILC DAMPING RING WIGGLER SECTION

The ILC damping ring electron cloud problem presents immense numerical challenges because of the large range of both spatial and temporal time scales in the problem. Assuming the beam distribution to be Gaussian in all three spatial dimensions, the damped beam is expected to have σ_y of about 4 μm. The vacuum pipe radius is 2.3 cm. The ratio of transverse scales is therefore ~ 2500. Longitudinally, $2\sigma_z$ is projected to be 1.8 cm, and the length of the wigglers in just one pass around the ring is 200 m, giving a ratio of longitudinal scales of 11,000. (Note that in this estimate we assume that the relevant simulation length per turn is the 200 m occupied by wigglers. In our simulations we intend to, at least initially, use maps rather than particle-in-cell simulation to move the beam from wiggler to wiggler.) The simulation will not be accurate unless the beam is spatially resolved, but a mesh that is 2500 x 2500 x 11000 requires 7 x 10^{10} mesh cells!

One answer to this huge range of scales is clearly mesh refinement, but it should be noted that the field gradient requires that the refinement extend transversely considerably past the region occupied by beam particles. In present runs simulating half a wiggler period (20 cm of wiggler), refined meshes of about 15 million cells are required around the beam in order to properly represent the electromagnetic fields.

The technique which will be used to ameliorate the problem of the large range of longitudinal spatial scales is calculation in a Lorentz boosted frame. In such a frame the length scale for the beam can be made commensurate with that of the wiggler period.

The range of temporal scales in the problem is also extremely large. The smallest timescale is that of an electron which, feeling the space charge potential of the beam, can reach a velocity ~ 1/3 c as it passes through the beam. In order to avoid numerical instability (i.e., in order to satisfy the Courant-Friedrichs-Levy condition) and to have the particle motion properly resolve the electromagnetic fields, the electron must not cross more than a fraction of a mesh cell in one simulation time step, Δt. If there are 10 mesh cells across $2\sigma_y$ of the beam, this means $\Delta t = 2 \times 10^{-14}$ seconds. Resolving the cyclotron motion is less difficult, since the cyclotron period for the wiggler peak field (1.67 T) is 2 x 10^{-11} s. The damping time of the beam ≈ 20 ms, so the range of temporal scales in the problem is twelve orders of magnitude.

Again, to ameliorate this temporal multiscale issue we plan to simulate in a Lorentz boosted frame. This reduces the transverse electron velocity, and it is possible to make this velocity commensurate with that required to satisfy the Courant-Friedrichs-Levy condition for the beam particles travelling at c in the z direction across mesh cells which resolve both the beam and the wiggler period. A moving frame with γ of 45, relative to the laboratory frame, will achieve this. Code changes to automate calculation in a boosted frame are in progress. Image currents from electrons, which in the boosted frame are travelling backward at $v \approx v_{frame}$, must be implemented for cases where the electron image currents are important. Wake fields for walls with finite conductivity have not yet been considered and are not implemented in WARP.

We estimate that using mesh refinement reduces CPU time requirements by approximately a factor of 10^4 from the uniform grid case. Calculating in a Lorentz boosted frame should save about a factor of 1000 in CPU time by allowing increased time step. The CPU time saving of the drift-Lorentz mover is a factor of 20-50, but in the Lorentz boosted frame it is not required. More computer time can possibly be saved by using different time steps for different particles as determined by the requirements of their dynamics-- another WARP feature -- but the CPU savings of this have not yet been explored. It is of course essential for this problem that a code run in parallel on as many processors as are available.

The above algorithms have been recently implemented in the WARP modules of WARP-POSINST, and we are in the process of extensively testing them for the physics of the ILC wiggler problem, and optimizing the numerous numerical parameters required.

PRELIMINARY RESULTS

We have produced preliminary results for the ILC damping ring wiggler using WARP-POSINST to study the buildup of the electron cloud in a half period of the wiggler. A non dynamically-evolving beam was used in order to reduce computer time. For the results discussed here the timescale is short enough that the beam would not be expected to evolve, so this approximation has physical justification.

A plot of the electron positions in the x-z plane after 50 bunch passages is shown in Fig. 1. For this case the bunches are Gaussian in x,y, and z, with σ_x = 40 μm, σ_x = 40 μm, σ_z = 6 mm, 2.07 x 10^{10} positrons per bunch, and one bunch passage every 7 ns. The peak wiggler field is 1.67 T; the wiggler period is 40 cm. The peak secondary yield is 1.4. For the purposes of illustration, no reflections of photons from the vacuum vessel have been allowed, so all photoelectrons are born just outside the antechamber slots and move on field lines there. There are therefore no electrons streaming vertically along field lines through the center of the chamber. In this plot one can see electrons crossing the chamber in the x direction at the field null. The main wiggler field is in the y

direction. Diagnosis of the results shows that many electrons in the vicinity of the field nulls travel in z more than a centimeter from the positions where they were born. These 3D effects are very interesting. It remains to be seen whether they will prove to be important in their effects on the beam. Since they occur with the periodicity of the wiggler half-period, it is possible that they can produce "structural resonances", therefore affecting the beam more than would be expected, given the proportion of longitudinal space occupied by this phenomenon. But even without such a resonance, this 3D motion occurs in about 10% of the wiggler length.

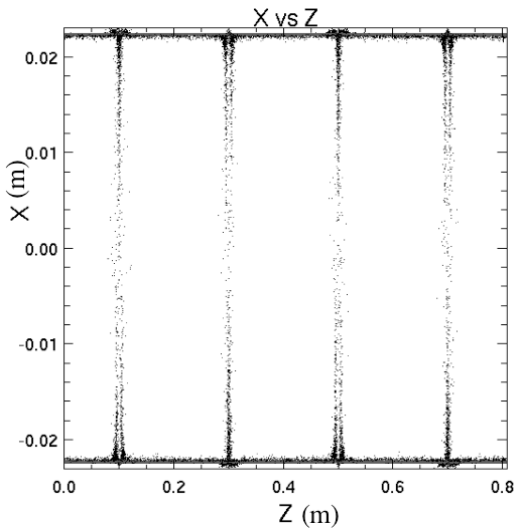

Figure 1: Electrons (black dots) streaming across the vacuum channel in the ILC wiggler at vertical field nulls after 50 bunch passages.Benchmark vs. posinst.

Benchmarking of the code against POSINST is in progress. Since POSINST is 2D (the system is infinitesimally thin in z), the problem chosen was an ideal dipole, with B = 1.6 T. In WARP particles were pushed only in x and y. The Bassetti-Erskine field approximation was used in both codes to compute the beam (but not electron) field. (We have checked the beam field calculated by the PIC algorithm in WARP against the Bassetti-Erskine result, and found the WARP field to be accurate.) The beam was given ILC parameters, with σ_x=112 μm, σ_y=4.6 μm, σ_z=6 mm, $2x10^{10}$ particles per bunch, and peak secondary yield of 1.4. Results are shown in Fig. 2. As can be seen, the two codes agree well for this case. Numerical convergence checks and comparison with 3D calculations will be done soon.

SUMMARY

We are using the WARP-POSINST particle-in-cell code to simulate electron cloud buildup in the ILC positron damping ring wiggler, and will later extend this to calculation of electron effects on the beam . WARP-POSINST is a 3D parallelized self-consistent code containing several algorithms that are necessary for the ILC problem. The electron cloud problem for the

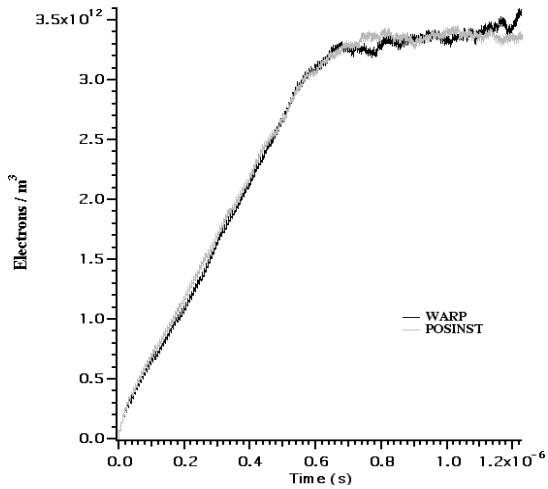

Figure 2. Electrons per m^3 (averaged over 2.3 cm radius beampipe) vs time in ideal dipole from WARP-POSINST and POSINST. 64x64 transverse grid. $\Delta t=5x10^{-12}$ s.

damping ring is a multiscale problem with very large ranges of both spatial and temporal scale. Mesh refinement is essential and reduces the required CPU time by about four orders of magnitude.

The smallest timescale in the problem is that of accelerated electrons crossing the beam. The technique of simulating in a Lorentz boosted frame can be used to make this timescale commensurate with the time step necessary to resolve the longitudinal motion of the beam through the wiggler, which will also reduce the length of the accelerator by a factor equal to the γ of the frame.

Preliminary WARP-POSINST results for electron cloud buildup in the wiggler section show 3D effects for a centimeter on either side of each null of the vertical wiggler field. This effect will be further quantified in the future. First results of a benchmark against POSINST show good agreement for an ideal dipole case.

REFERENCES

[1] J.-L. Vay, M. A. Furman, P. A. Seidl, R. H. Cohen, A. Friedman, D.P. Grote et. al., NIMPR A 577, 65 (2007).

[2] D.P. Grote, A. Friedman, I. Haber, W. Fawley, J-L. Vay, "New Developments in WARP: Progress towards end-to-end simulation", Nuc. Instr. & Meth. A **415**. 428-432 (1998).

[3] M. A. Furman and G. R. Lambertson, "The Electron-Cloud Instability in the Arcs of the PEP-II Positron Ring", Proc. Intl. Workshop on Multibunch Instabilities in Future Electron and Positron Accelerators (MBI-97), KEK, Tsukuba, Japan, 15-18 July 1997, KEK Proceedings 97-17, Dec. 1997 (Y. H. Chin, ed.), p. 170.

[4] M. A. Furman and M. T. F. Pivi, "Probabilistic Model for the Simulation of Secondary Electron Emission", PRSTAB/v5/i12/e124404 (2003). (http://prst-ab.aps.org/pdf/PRSTAB/v5/i12/e124404).

[5] R.H. Cohen et. al, Phys. Plasmas **12**, 056708 (2005).

[6] J.-L. Vay, Phys. Rev. Lett. **98**, 130405 (2007).

