

USING WARP-POSINST FOR CALCULATION OF THE ELECTRON CLOUD IN THE ILC POSITRON DAMPING RING WIGGLERS *

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Abstract

The electron cloud in the positron damping ring of the International Linear Collider (ILC) presents a severe design constraint for the ring unless mitigations can sufficiently reduce the cloud density. The most intense cloud is expected to be found in the wiggler sections. The self-consistent code suite WARP-POSINST is being used to study this problem. 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, a drift-Lorentz large time step electron mover, and the use of a moving reference frame for the calculation will all be employed to reduce the computer time needed by several orders of magnitude. Preliminary results are shown which indicate 3D electron effects at nulls of the vertical wiggler field.

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, in order to precisely determine the thresholds for instability or emittance growth caused by the cloud.

The most intense electron cloud is expected to occur in the dipole and wiggler sections of the damping ring, where beam synchrotron radiation will produce copious photoelectrons. Dynamics of the electrons 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 the ways that we expect to meet these challenges using new algorithms in WARP-POSINST. And lastly we show preliminary first results from the code for the case of cloud buildup for a nondynamical beam.

THE WARP-POSINST CODE SUITE

The WARP-POSINST code suite was made by combining the U.S. Heavy Ion Fusion Virtual National Laboratory code WARP with the electron cloud buildup code POSINST, which contains detailed models of electron production. The code suite is run via the Python interpreter, which enables the user to choose which routines from each code are used; to direct the progress of the calculation; to access variables from internal arrays of each code; and to write diagnostics concerning these variables in Python, without meddling with the internals of either code. WARP-POSINST, as well as WARP and POSINST, have been described elsewhere [1-6], and we will give details here only as they pertain to calculation of the electron cloud effect in the ILC.

For this paper, the code was run in a mode that used WARP to manage and calculate the electromagnetic fields and the particle dynamics. POSINST routines were called from Python or by WARP to create photoelectrons 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, with the electric and magnetic fields being calculated for the time-dependent distribution of macroparticles by solving Maxwell's equations for the charge and current densities given by the macroparticle positions and velocities. Radiation and retardation of the fields are neglected, but inductive effects are calculated to leading order. 2D and quasi-static models are also available within WARP, as well as the option of using a nondynamical (i.e., non-evolving) beam. Conducting boundaries around the system can have arbitrary shape—they are modelled using cut-cell methods. However the 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., the ability to increase the spatial resolution in selected areas of the mesh on which the electromagnetic fields are calculated. The ILC beam, for instance, because of its high charge density and small transverse dimensions, creates an extremely steep transverse electric field gradient within a few sigma of the beam. It is important to resolve that gradient with mesh cells of length comparable to the gradient scale length. But using this resolution throughout the spatial extent of

the problem would make it intractable because of CPU time and memory requirements. Refining the mesh (i.e., reducing its cell length) only where necessary is vital to simulation of the electron cloud problem in high-energy physics accelerators. Mesh cells in WARP-POSINST may also be of different length along different axes, as required by the physics. 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 used and found to result in an accurate calculation of the field. In the test case a beam moving at relativistic velocity with a Gaussian distribution function in x, y, and z was used, and the field calculated by WARP was compared to values given by the Bassetti-Erskine formula.

Several new algorithms have been added to WARP in the past two years in order to optimize it for heavy ion fusion and electron cloud calculations. The first of these is a “drift-Lorentz” mover [7]. This algorithm can be used to track the movement of particles in magnetic fields using a time step that is several times larger than cyclotron period. The Larmor radius of the orbit and progress of the gyrocenter are accurately calculated, though the phase of the particle is not. Thus the space charge from a collection of electrons in a magnetic field, for instance, is calculated correctly without having to decrease the simulation time step 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 [7] 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

We have chosen to simulate the electron cloud in the wiggler section of the ILC positron damping ring, because in this area the fields are inherently 3D, and therefore we believe that WARP-POSINST can make a contribution that is at this point unique.

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. Considering the beam to be a Gaussian in all three spatial dimensions, the damped beam will have σ_y of about 4 μm , while 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. The ratio is much higher if the simulation takes place over the full 6.7 km circumference, but 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 7×10^{10} mesh cells!

One answer to this huge range of scales is clearly mesh refinement, but it should be noted that the refinement must extend transversely past the region occupied by beam particles, since the gradient of the electric field requires rather fine spatial resolution considerably outside the beam. It will also be important to use simulations of small longitudinal sections of wiggler to understand cloud buildup and other local phenomena, so as to avoid as much as possible having a mesh that covers 200 m of wiggler. 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 $\sim 1/3 c$ 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, it is important that the electron not cross more than a fraction of a mesh cell in one simulation time step. If there are 10 mesh cells across $2\sigma_y$ of the beam, this means a time step of 2×10^{-14} seconds. Resolving the cyclotron motion is less difficult, since the cyclotron period for the wiggler peak field (1.67 T) is 2×10^{-11} s. The damping time of the beam is approximately 20 ms, so the range of temporal scales in the problem is twelve orders of magnitude.

Again, the solution we will use to ameliorate this temporal multiscale issue is calculation in a Lorentz boosted frame. Going to a relativistically moving frame 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 the 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. Note that in this frame the cyclotron period is also resolved by the time step required by the Courant-Friedrichs-Levy condition

for the longitudinal motion of the beam. At present it is possible with WARP-POSINST to simulate in the boosted frame by inputting the initial conditions of the beam and wiggler appropriate for the boosted frame. Soon the conversion to boosted frame will be automated, requiring only that the user input initial conditions in the laboratory frame and the relativistic γ of the chosen boosted frame. Image currents from electrons, which in the boosted frame are travelling backward with respect to the beam at $v=c$, must be examined and implemented also 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 the use of mesh refinement reduces CPU time requirements by approximately a factor of 10,000 from the case where the required resolution is implemented throughout using a uniform grid. Calculating in a Lorentz boosted frame should save about a factor of 1000 in CPU time by allowing increased time step. When it is used, the CPU time saving of the drift-Lorentz mover is a factor of 20-50, but in the Lorentz boosted frame this mover is not required. It is possible that more computer time can be saved by using different time steps for different particles, as determined by the requirements of their dynamics-- another feature of WARP-- but the computer savings which might ensue have not been explored as yet. It is of course essential for a code approaching this problem to 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.

We are currently benchmarking the code against POSINST for the case of electron cloud buildup in an ideal dipole-- i.e., a constant vertical field. This case has been chosen because POSINST is a 2D code, but the simulation will be done in 3D with WARP-POSINST.

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 shown 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 $\sigma_x = 40 \mu\text{m}$, $\sigma_x = 40 \mu\text{m}$, $\sigma_z = 6 \text{ mm}$, 2.07×10^{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 show that many electrons in the vicinity of the field nulls travel in z more than a centimeter from the position where they are 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.

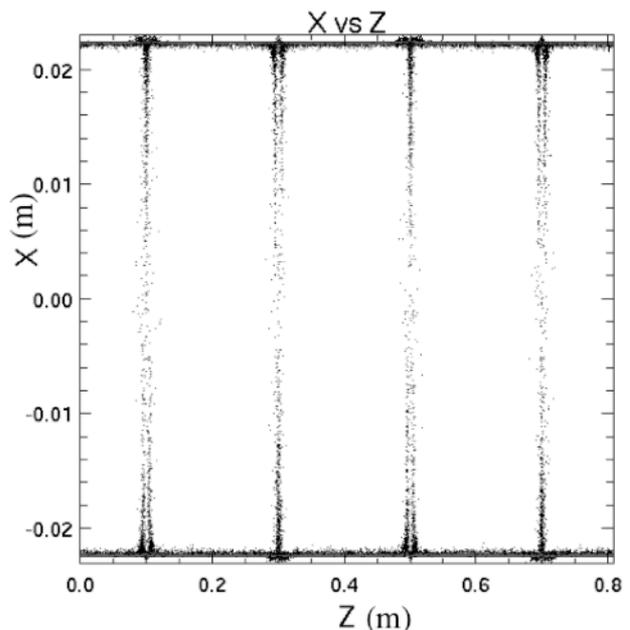


Figure 1: Electrons streaming across the vacuum channel in the ILC wiggler at nulls of the vertical field after 50 bunch passages. Each black dot is a macroelectron.

SUMMARY

We are beginning to use the WARP-POSINST particle-in-cell code to simulate the electron cloud buildup and its effects on the beam in the ILC positron damping ring wiggler. WARP-POSINST is a 3D parallelized code containing several algorithms that are necessary for the ILC problem. The electron cloud problem for the 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 of γ .

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.

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