SIMULATIONS OF PULSE PROPAGATION IN THE LASER WAKEFIELD ACCELERATOR USING A MASSIVELY-PARALLEL OBJECT-ORIENTED PARTICLE IN CELL CODE

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Abstract

A two-dimensional relativistic electromagnetic particle-in-cell code XOOPIC [1] was modified to allow the simulation of laser plasma interactions. The object-oriented implementation of the code makes relatively simple the task of extending and including new physics into the original code. A new class was created to allow launching of laser pulses with a Gaussian profile and linear polarization from either boundary. Because only the region of the plasma near the laser pulse is of interest, a computational moving window was introduced in the original code to follow the evolution of the laser pulse. An implementation of the moving window to run in MPI-based parallel machines was also developed. The modified code was used to simulate the propagation of a single laser pulse through a plasma and the electron injection into a plasma wakefield by colliding laser pulses.

1 INTRODUCTION

Plasma-based accelerators have received much theoretical and experimental attention in the last decade due to the large high longitudinal electric fields that can be excited in a plasma without the limitations found in conventional accelerators. Many different plasma-based accelerator schemes have been proposed since the late seventies [2]. One widely investigated and very promising concept is the laser wakefield accelerator (LWFA). Recently, a new method for injecting electrons in a LWFA has been proposed [3] that uses two laser pulses, which propagate either perpendicular or parallel to one another. When the injection pulses collide, a slow phase velocity beat wave is generated that injects electrons into the fast wake field for acceleration.

Some preliminary theoretical analysis and simulations in one-dimensional space have been done to study the colliding laser pulses scheme [9], but to fully understand the complex phenomena involved, full two-dimensional scale simulations will be requiered. We chose to make use and modify an existing proven code, XOOPIC, to perform the laser wakefield accelerator simulations. The rest of the paper is organized as follows: in Sec. 2 a brief description of XOOPIC code with the modifications we made is given. In Sec. 3 we described the injection laser scheme. In Sec. 4 we present the results of the simulations, and summary and conclusions are presented in Sec. 5.

2 THE XOOPIC CODE

XOOPIC is an object-oriented two-dimensional relativistic electromagnetic particle-in-cell code written in C++ by J. P. Verboncoeur and collaborators at the University of California at Berkeley [1]. The XOOPIC code has implemented Cartesian and Cylindrical geometries. It can handle electrostatic and electromagnetic simulations and relativistic and non-relativistic particles. The code also has a partial implementation to run on MPI-based parallel machines. XOOPIC was designed to be user-friendly. It comes with a sophisticated graphical user interfase (GUI) and an expert system advisor. The particles follow the relativistic equations of motion in electric and magnetic fields, generating a source current for the field equations. The particles ae advanced using the relativistic time-center Boris scheme [4]. The code uses a charge conserving current weighting algorithm, which ensures that Gauss' law remains satisfied if it was initially satisfied.

The nature of the problems we want to address necessitate an understanding of the evolution of an intense short laser pulse propagating through a plasma. Because only the region of the plasma near the lase pulse is of interest, we need to follow the evolution of the laser pulse using a computational moving window which moves with the laser pulse at approximately the speed of ligth. We also need the code to allow launching a Gaussian electromagnetic wave from a boundary to simulate a laser beam entering the plasma.

Neither of these two requirements were implemented in the original version of XOOPIC, therefore our first task was to modify XOOPIC to include these capabilities. The object-oriented implementation of the code makes relatively simple the task of extending and including new physics into the orignal code. A computational window that moves with the speed of light was include into XOOPIC using a cyclic mesh technique. The window is moved by removing columns of cells and particles from behind the pulse and placing them at the front of the pulse with new particles. The cycling rate is chosen so that the grid moves at the speed of light. Typically, it will take many time steps for the window to move one cell length. We wait until the pulse travels one cell-size to move the grid. The moving window algorithm was implemented to run on MPI-based parallel machines. A new method *shiftFields()* is introduced in the Field class to update the field magnitudes and a new method, *shiftPart()*, is introduced in the ParticleGroup class to update the positions of particles after moving the computational window. The problem of launching a Gaussian electromagnetic wave from a boundary was solved by creating a new derived class *portgauss*, which inherits from an existing boundary class *port*.

3 LASER WAKE FIELD ACCELERATOR SCHEMES

The accelerating electric field (or gradient) in conventional radio frequency linear accelerators is limited to around 100 MV/m, partly due to heating or breakdown on the walls of the structures. In order to accelerate electrons to very high energies (greater than 1 TeV) without building a too long and too expensive structure, it is necessary to develop new acceleration concepts providing a higher accelerating electric field. Plasmas can support large high longitudinal electric fields. More precisely, ionized plasmas can sustain electron plasma waves (EPW) with longitudinal electric field on the order of the nonrelativistic wavebreaking field [5], $E_0 = cm_e\omega_p/e$. For an electron density of $n_e = 10^{18}cm^{-3}$ the electric field is $E_0 \approx 100GV/m$ (which is approximately three orders of magnitude greater that obtained in conventional RF linacs) with a phase velocity close to the speed of light.

The use of the ponderomotive force associated with a laser pulse to excited an EPW was first proposed by Tajima and Dawson [2]. In the laser wakefield accelerator (LWFA), a single short ($\leq 1ps.$), ultrahigh intensity ($\geq 10^{18}W/cm^2$) laser pulse injected in an underdense plasma excites an EPW behind the pulse. The plasma wake is excited by the ponderomotive force created by the photons. A correctly placed trailing electron bunch can be accelerated by the longitudinal electric field and focused by the transverse electric field of the plasma wake. Although several recent experiments [6] - [8] have demostrated the self-trapping and acceleration of electrons, the production of electrons beams with low momentum spread and good pulse-to-pulse energy stability will requiere injection of ultrashort electron bunches into the wake field with femtosecond timing accuracy. These requirements are beyond the current state-of-the art performance of photocathode radiofrequency electron guns.

Recently a method for injecting electrons in a LWFA has been proposed [3] that uses two laser pulses which propagate either perpendicular or parallel to one another. The colliding pulse scheme uses three short laser pulses. An intense pump pulse generates a fast ($v_{p0} \approx c$) wake field. A forward going and a backward going injection pulses collide at some distance behind the pump pulse generating a slow ponderomotive beat wave with phase velocity $v_{pb} \approx \Delta\omega/2k_0$. During the time in which the two injection pulses overlap, the slow beat wave injects plasma electrons into the fast wake field for acceleration to high energies. Injection and acceleration can occur at low densities ($\lambda_p/\lambda \approx 100$), thus allowing for high single-stage energy gains. The colliding pulse scheme offers detailed control of the injection process. The injection phase can be controlles via the position of the forward injection pulse, the beat phase via $\Delta\omega$, the injection energy via the pulse amplitude, and the number of trapped electrons via the backward pulse duration.

4 SIMULATIONS RESULTS

In order to test the modifications we made to the code, we simulated the propagation of a laser pulse through underdense plasma. The parameters used in the simulation were the following: the electron plasma density was $n_{e0} = 6.9 \times 10^{17}cm^{-3}$ which corresponds to a wavelength of $\lambda_p = 40\mu m$ and to a plasma frequency $\omega_p = 4.7 \times 10^{13}s^{-1}$.

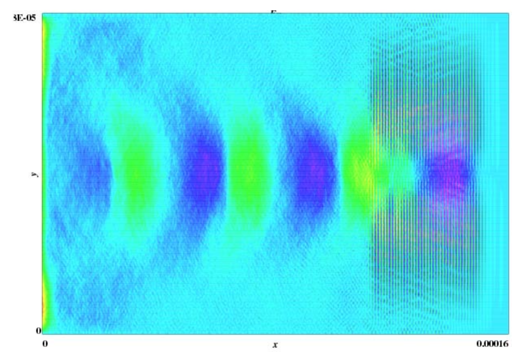

Figure 1: Longitudinal electric field as a function of distance

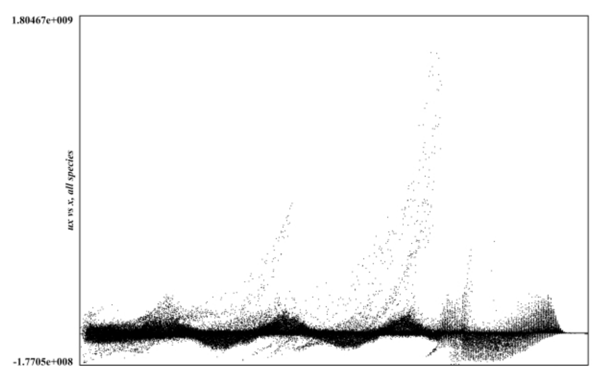

Figure 2: Snapshot of electrons in phase-space.

The laser pulse was chosen to be linearly polarized with a transverse Gaussian profile. The minimum laser spot size is $20\mu m$ and the Rayleigh length is about $31\lambda_p$. In order to maximize the amplitude of the wake field, the laser pulse length was chosen to be about λ_p [3]. The laser intensity was taken to be $I_L = 1.0 \times 10^{18}W/cm^2$ and the laser wavelength $\lambda_0 = 1\mu m$. The length of the simulation box was $L_x = 120\mu m$ in the x direction and $L_y = 80\mu m$ in the y direction. The computational mesh consisted of 1200 cells in the x direction and 225 cells in the y direction. The simulation used about 270000 particles.

Fig. 1 shows a contour plot of the longitudinal electric field as a function of distance. The plasma wake can be clearly seen behind the laser pulse. Fig. 2 is a snapshot of electrons in phase space taken at the same time as Fig. 1. The acceleration of electrons trapped in the plasma wake can be clearly observed in this figure.

The parameters used in the colliding pulses simulation were the same as in Schroeder's paper [9]. The electron plasma density was $n_{e0} = 6.9 \times 10^{17} cm^{-3}$ which corresponds to a wavelength of $\lambda_p = 40 \mu m$ and to a plasma frequency $\omega_p = 4.7 \times 10^{13} s^{-1}$. The laser pulses were chosen to be linearly polarized with transverse Gaussian profile. The minimum laser spot size is $15 \mu m$ and the Rayleigh length is about $22 \lambda_p$. In order to maximize the amplitude of the wake field, the laser pulse length was chosen to be about λ_p [3]. The pump laser intensity was taken to be $I_L = 1.0 \times 10^{18} W/cm^2$ and the laser wavelength $\lambda_0 = 0.8 \mu m$. The forward injection laser pulse has a wavelength $\lambda 1 = 0.83 \mu m$ and the backward $\lambda_2 = 0.8 \mu m$. The pulse length is $\lambda_p/2$ for both injection pulses. The length of the simulation box was $L_x = 160 \mu m$ in the x direction and $L_y = 90 \mu m$ in the y direction. The computational mesh consisted of 1600 cells in the x direction and 150 cells in the y direction. The simulation used about 240000 particles.

Figures 3 to 5 are snapshots of electrons in phase-space at different stages during the collision of the injection pulses. We observed that during the collision, the beating of the injection laser pulses picks up some electrons from the background plasma. However, we were unable to observe electrons get trapped into the plasma wake and get accelerated.

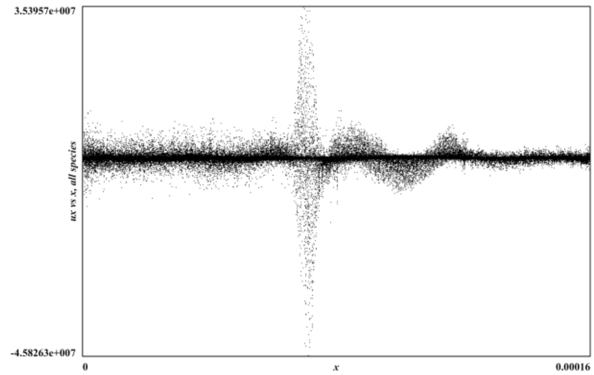

Figure 4: Snapshot of electrons in phase-space while the injection pulses are colliding.

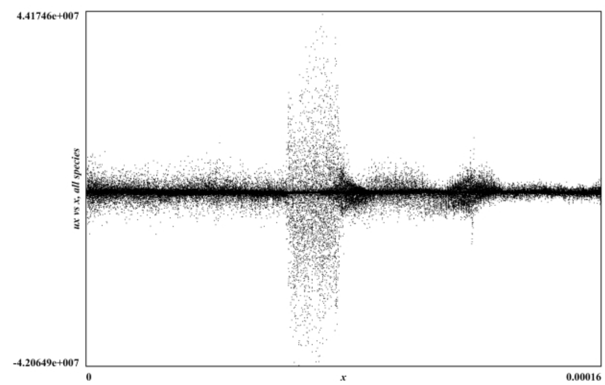

Figure 5: Snapshot of electrons in phase-space after the injection pulses collide.

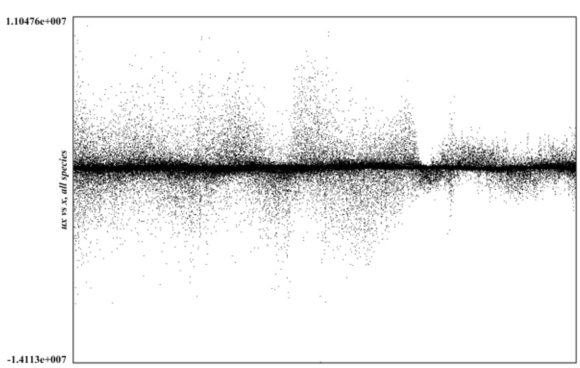

Figure 3: Snapshot of electrons in phase-space before the injection pulses collide.

5 CONCLUSIONS

The XOOPIC code was modified to allow the simulations of laser-plasma interaction processes. A new class was created to allow launching of laser pulses with Gaussian profile from a boundary and a moving computational window was introduced to follow the evolution of a laser pulse. The propagation of a single ultrashort, high intensity pulse through a plasma was simulated. The acceleration of electrons trapped in the plasma wake can be observed. The electron injection into a plasma wakefield by colliding laser pulses was also simulated. We observed that the beating of the injection laser pulses picks up some electrons from the background plasma. However, we could not see electrons get trapped and accelerated by the plasma wake.

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