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Modeling of Ionization Physics with the PIC Code OSIRIS

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Abstract. When considering intense particle or laser beams propagating in dense plasma or gas, ionization plays an important role. Impact ionization and tunnel ionization may create new plasma electrons, altering the physics of wakefield accelerators, causing blue shifts in laser spectra, creating and modifying instabilities, etc. Here we describe the addition of an impact ionization package into the 3-D, object-oriented, fully parallel PIC code OSIRIS. We apply the simulation tool to simulate the parameters of the upcoming E164 Plasma Wakefield Accelerator experiment at the Stanford Linear Accelerator Center (SLAC). We find that impact ionization is dominated by the plasma electrons moving in the wake rather than the 30 GeV drive beam electrons. Impact ionization leads to a significant number of trapped electrons accelerated from rest in the wake.

Motivation

Ionization is important in plasma sources for plasma-based accelerators. With shorter electron beams and higher intensity laser beams becoming available, simulating and understanding the physical effect of ionization becomes more and more important for nearly every plasma source except fully ionized hydrogen. In the upcoming E164 Plasma Wakefield Accelerator experiment at SLAC, a short (.1 mm) but high current electron bunch is proposed to drive plasma wakefields in a partially ionized Li plasma. To achieve the optimal wake amplitude, a high-density plasma and gas (exceeding 10^{15} cm $^{-3}$) is required. Ionization by the electron beam or plasma electrons may not be ignored in this case.

In this paper, we introduce the algorithm of adding an ionization package (focused on impact ionization only at this stage) into the 3-D object-oriented fully parallel PIC code OSIRIS[1]. Simulation results of the creation of new electrons, electron trapping and simulation for E164 are also presented. Adding tunnel ionization and benchmarking the results with XOOPIC will be discussed in future publications.

Impact ionization module

Figure 1 shows a simple module for impact ionization. Collisions are implemented in OSIRIS with a Monte Carlo collision (MCC) package including the null collision method [2]. For the MCC, the probability for a particle to ionize the gas is:

$$P_i = n_g\sigma(v_i)|v_i|\Delta t \qquad (1)$$

Here, n_g is gas density, σ is gas cross-section, v_i is the velocity of the i_{th} incident particle. We compare a random number between 0 and 1 with this probability, if Random $(0,1)<P_i$, ionization does occur, decreases the gas density

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and creates a new electron and neutralizing ion.

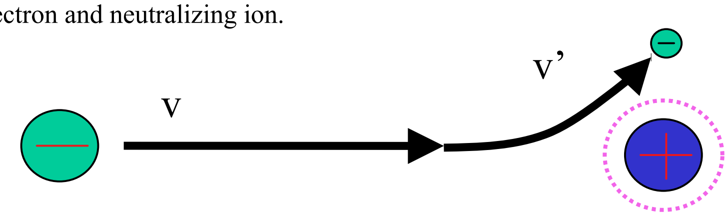


FIGURE 1. Simple model for impact ionization: Particles injected into gas may ionize the gas and create new electrons and ions.

The Osiris PIC code

Osiris is a 3D fully relativistic PIC code. It consists of modules. Each module is independent, and can exchange information with other modules. This structure enables us to very easily add a new module for a gas species, and this new gas module can interact with other modules to realize ionization.

Simulation Results

A. Test problem with 2D Cartesian Geometry

Plasma and gas come into a moving window from the right side. The beam stays at the center of the simulation window. Simulation parameters are: simulation box 18*6c/ω_p, grid 180*60, 9 particles per cell, dt=0.07/ω_p, t_{max}=19/ω_p. We set plasma density to be uniform, and the gas can be fully ionized.

We simulate both electron beam and positron beams; the comparison is shown in Fig. 2:

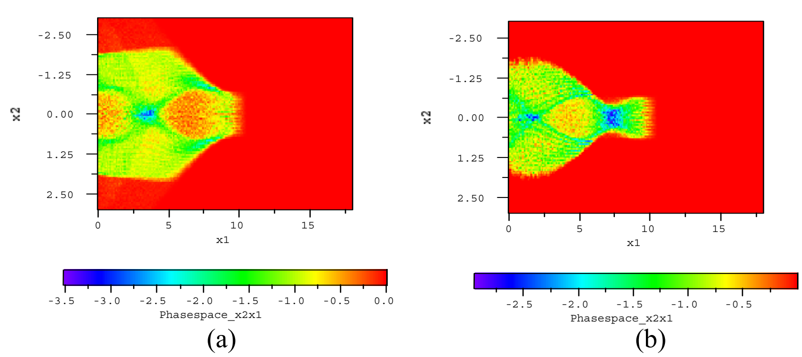


FIGURE 2. Real space density of newly created electrons for (a) electron beam, (b) positron beam. In both cases, new electrons are created, but for the positron beam, the new created electrons are sucked to the center of the beam.

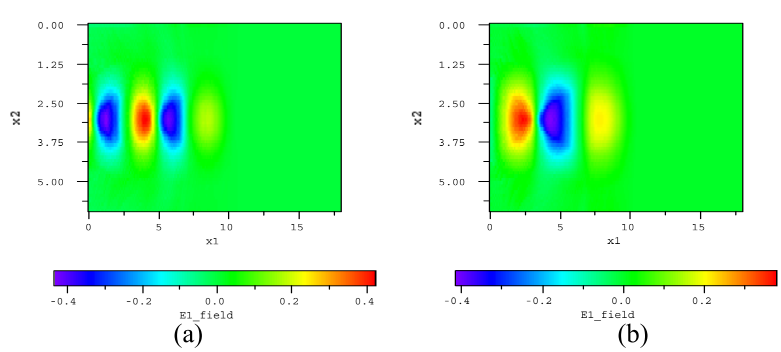
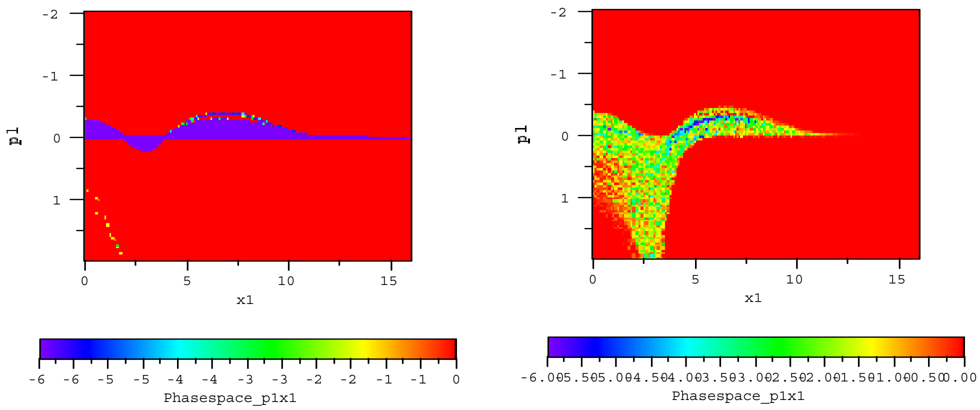


FIGURE 3. Comparison of longitudinal electrical field between (a) with ionization and (b) without ionization.

Figure 3 shows the wavelength changing after ionization is turned on. The wavelength of wake field becomes shorter because the new created electrons increase the plasma density.

B. Electron trapping in a 3D simulation

It is predicted that when born at the proper phase, the new created electrons can be trapped by the excited plasma wake. We simulate a 3D case in which new created electrons are observed to gain more energy than background plasma electrons as Fig. 4 shows.



(a) (b)

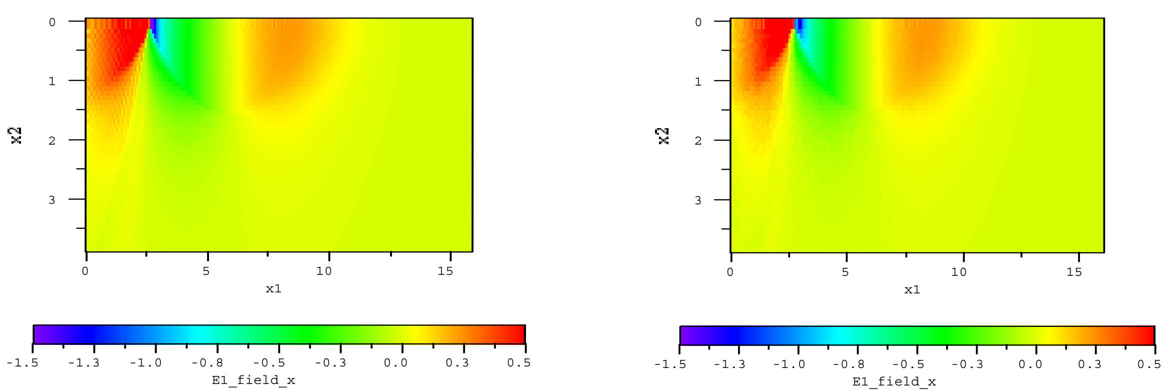
FIGURE 4. Phase space P1X1 of (a) background plasma and (b) newly created electrons. The electrons with normalized momenta $P1=p_z/mc > 0.4$ have been trapped and accelerated by the wave. Note that momentum increases downward in these plots.

C. Modeling the E164 experiment

The parameters of the upcoming E164 Plasma Wakefield Experiment and corresponding simulations are shown in the table 1 below.

Table 1.

Physical parameters						Simulation paramenters			
$n_{plasma}(cm^{-3})$	$n_{gas}(cm^{-3})$	E_{beam}	N	σ_z	σ_r	dt	t_{max}	grids	coordinates
$5*10^{15}$	$3*10^{16}$	30Gev	$2*10^{10}$	100μm	25μm	.022	22	400*200	2D cylindrical



(a) (b)

FIGURE 5. The longitudinal electron field of the wake (a) without ionization, (b) with ionization. There is little difference between them.

In this experiment, the laser-ionized Li vapor plasma is not fully pre-ionized by the laser. The remaining neutral gas density is nominally six times the ionized density.

To study the effect of impact ionization of the gas on the experiment, we model several cases. First, we examine the effect of the impact ionization due to both the beam (primary) and the blown out plasma (secondary ionization). We find that the fractional ionization from impact ionization of the neutral gas is up to 4%, corresponding to an increase in plasma density of $0.24*10^{15}$ cm^{-3}. The effect of this density on the electric field of the wake is minimal (Fig 5). Including ionization in the model increases the wake wavelength by 1.4% and decreases the amplitude by 9% at $3\sigma_z$. The spike electric field is decreased by 36%. However, the spike value is not useful for acceleration experiments since it contains very little energy. Next, we isolate the source of the ionization in the modeled experiment by including the primary or secondary ionization process only. We find that plasma ionization dominates beam ionization by a factor of order 400. This is because the cross-section for ionization of gas is peaked near 10 eV and drops sharply as energy increases [3]. We also estimated the number of trapped electrons after 1.65 mm of propagation. Less than 0.01% electrons are trapped. This number will increase as new electrons are continually created and trapped over the 30 cm design length.

Summary

We added impact ionization into the code OSIRIS, and presented 2D and 3D simulation results. In both cases, we see the creation of new electrons, change of wake wavelength and trapping of newly created electron. Also, we conclude that impact ionization will occur but may have little effect on the wakes in experiment E164. Because of the lower cross-section at higher energy, plasma ionization dominates beam impact ionization.

Acknowledgments

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