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ELECTRON OSCILLATIONS IN THE INTENSE LASER PRODUCED THREE-DIMENSIONAL POST-SOLITON ELECTROMAGNETIC FIELD

Dongning Yue, Xiaohui Yuan, Min Chen†
Key Laboratory for Laser Plasmas (Ministry of Education), School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China
Collaborative Innovation Center of IFSA, Shanghai Jiao Tong University, Shanghai, China

Abstract

Electron oscillations in the three-dimensional post-soliton electromagnetic field generated by ultrashort intense laser in near-critical density plasma were studied using 3D particle-in-cell (PIC) simulations. Two types of post-solitons were observed. We found that unlike the ions, which are expelled from the centre of post-soliton, electrons oscillate around the centre of a post-soliton and the resultant poloidal electric vector field behaves like an oscillating electric dipole. The toroidal magnetic field also oscillates along with electrons. On the timescale of ω_{pi}^{-1}, where ω_{pi} is the ion plasma frequency, protons have evolved into multi-shell structures due to Coulomb explosion in the post-soliton. The polarization of the post-soliton is found to be different from that of the driver laser beam.

INTRODUCTION

Nonlinear localized coherent electromagnetic (EM) modes have been found in the interaction of ultra-intense ($I \geq 10^{18}$ Wcm^{-2}) laser pulse with underdense plasma ($\omega_{pe} < \omega_L$, where ω_L is the laser frequency, $\omega_{pe} = \sqrt{4\pi n_e e^2/m_e}$ is the electron plasma frequency, n_e is the electron density). A laser pulse depletes its energy into plasma on a spatial scale of the order of $l_{depl} \approx l_{pulse}(\omega_L/\omega_{pe})^2$ during propagation, where l_{pulse} represents the laser pulse length [1]. With the laser energy loss, the laser frequency undergoes a redshift. The laser experiences locally overcritical density plasma and is trapped in the plasma cavity. This coherent structure shows excellent stability in one-dimensional PIC simulation and propagates with a velocity that is well below the speed of light or almost equal to zero in homogeneous plasma [2]. Since the low frequency EM wave confined inside the slowly expanding plasma cavity is normally generated in the wake of the driver laser pulse, it is therefore denoted as "post-soliton".

A model called "snowplow" has been proposed to explain the generation and evolution of the two-dimensional *s*-polarized post-soliton [3, 4]. Experimental and PIC simulation results show that the structure of the three-dimensional post-soliton is anisotropic like a prolate spheroid [4, 5] and depends on the plasma parameters [6].

In this paper, the EM field structure of the three-dimensional post-soliton, electron oscillations in this field and multi-shell like structure of protons will be presented. The polarization of post-soliton is different from that of laser, which has not been reported before as far as we know.

SIMULATION RESULTS

Three-Dimensional Particle-In-Cell (3D-PIC) code OSIRIS was used in this study [8]. In the simulation, the laser pulse propagates along x_1 direction and is linearly polarized along x_2 axis. The normalized electric vector is $a = eE/(m_e\omega c) = 1$ with pulse duration of 40 fs corresponding to 15 T_0 which $T_0 = \lambda_0/c$ and laser wavelength λ_0 is 0.8 μm. The laser pulse has a transversely Gaussian envelope and its focal plane is at a distance of 20 μm from the back of plasma slab. The laser pulse starts at x_1 = 15 μm (the front of the plasma slab). The plasma slab is 30 μm thickness and the homogenous density is $n_e = 0.28\, n_{cr}$. The simulation box is $x_1 \times x_2 \times x_3$ = 45 μm $\times$ 14 μm $\times$ 14 μm and is divided into 900 $\times$ 280 $\times$ 280 cells. Protons are set to be mobile in the simulations.

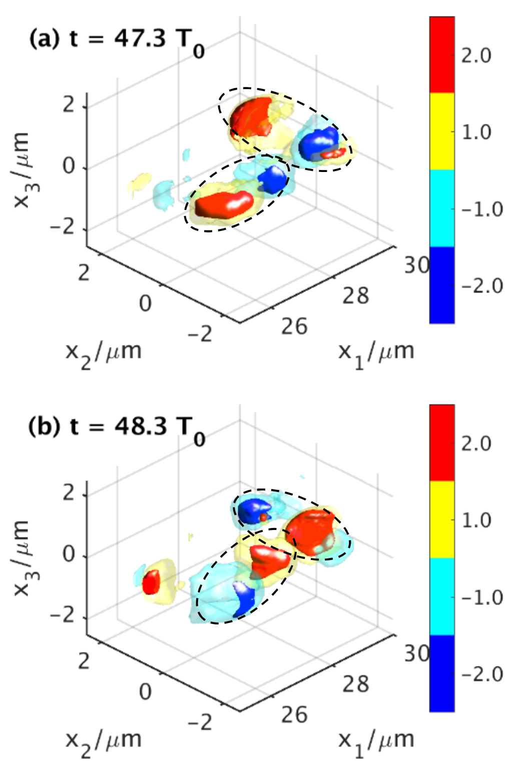

Figure 1: Distributions of transverse electric field E_2 at t = 47.3 T_0 (a) and t = 48.3 T_0 (b), respectively. Dotted line areas highlight the electric fields that are trapped inside the post-soliton structure.

† minchen@sjtu.edu.cn

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Figure 1 shows the distributions of transverse electric field E_2 at two time snaps after the laser pulse arrival. Part of the electric field is trapped inside the post-soliton structure and oscillates like a standing wave. Two different modes are observed. One oscillates along x_1 direction (i.e. the laser propagation axis), and the other along x_2 direction (i.e. along laser polarization direction). Both post-soliton modes oscillate in a frequency lower than that of the driver laser.

We denote the post-soliton that oscillates along x_2 direction as transverse post-soliton and the other as longitudinal post-soliton. Figure 2 shows the transverse electron density distributions of the transverse post-soliton in the middle plane for two time snaps. It is clear that the structure elongates along the laser polarization direction. When electrons concentrate on one side, the other side will be a proton cavity. The cavity size is 2 μm in x_3 direction and 4 μm in x_2 direction, respectively. The concentrated electron density could be as high as 1.5 n_c, while the electron density on the wall is 0.84 n_c.

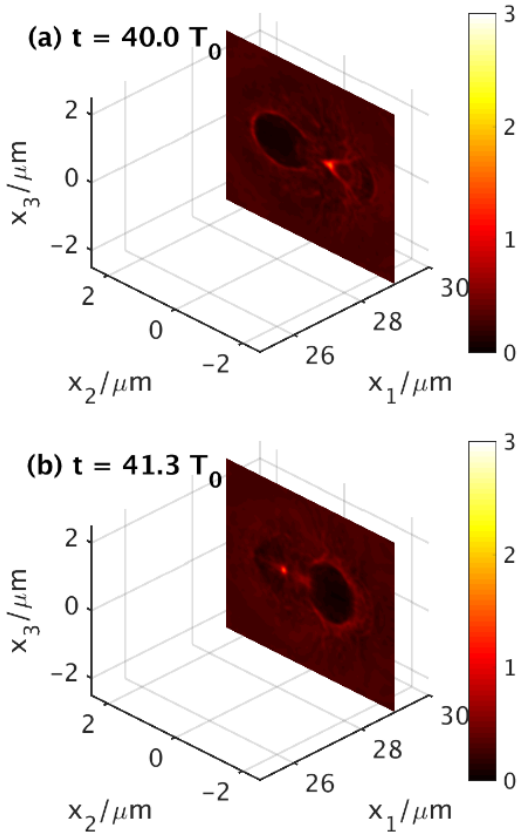

Figure 2: Electron density distributions of transverse post-soliton at t =40.0 T_0 (a) and t = 41.3 T_0 (b). The cross section is at x_1=29.0 μm and the density is normalized with critical density n_c.

The electric vector field distributions are shown in Fig. 3 at the same time as in Fig. 2. This electric vector field oscillates like an electric dipole, i.e. its poles follow the electrons' movement shown in Fig. 2. This field also shows the anisotropic structure.

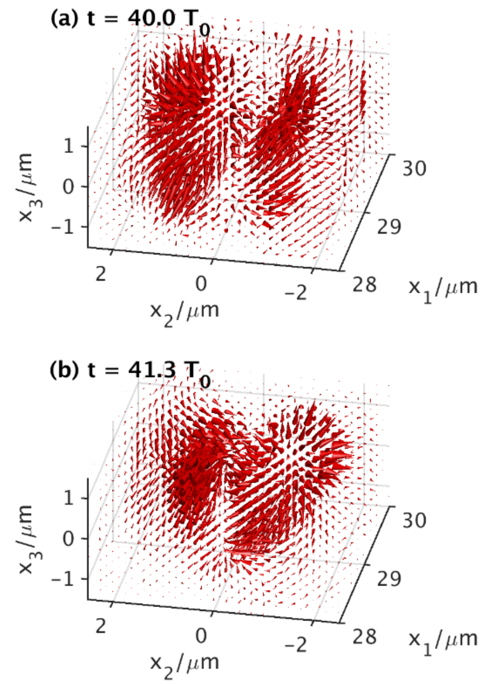

Figure 3: The electric vector field distributions inside transverse post-soliton at t = 40.0 T_0 (a) and t = 41.3 T_0 (b). The strength of electric field has been normalized.

The vortex-like magnetic field structure was shown in Fig. 4, which has a similar oscillation mode to Fig. 2 and Fig. 3. The toroidal direction of magnetic field is counter-clockwise with respective to the $+x_1$ direction.

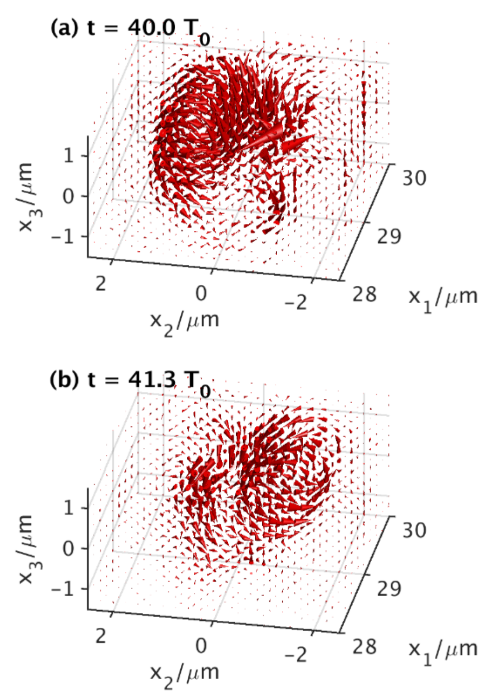

Figure 4: The magnetic vector field distributions inside the transverse post-soliton at t = 40.0 T_0 (a) and t = 41.3 T_0 (b). The strength of magnetic field has been normalized.

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In Fig. 5 we show the phase space distribution of protons in the transverse post-soliton. Protons are accelerated by the field inside the post-soliton. This process resemble to Coulomb explosion, which drives the cavity expanding slowly. We could see clearly there are two (three at most) antisymmetric regions both in p_2x_2 and p_3x_3 phase spaces. This suggests that at least two proton shells exist in the post-soliton structure. Protons pile up on the wall of the cavity and are pushed away from the cavity centre. More protons are involved in this process and start to move along the expanding direction. Protons could be accelerated to tens of keV energy on the cavity wall at time t = 68.8 T_0. The inner shell distribution of protons in p_2x_2 space is not as antisymmetric as in p_3x_3 space. This could be attributed to the influence of the other nearby post-soliton. Unlike the multi-shell structure found in electron vortex, which leads to a number of multi-stream instabilities, no instability is found in the process of post-soliton evolution in our simulation time window [7].

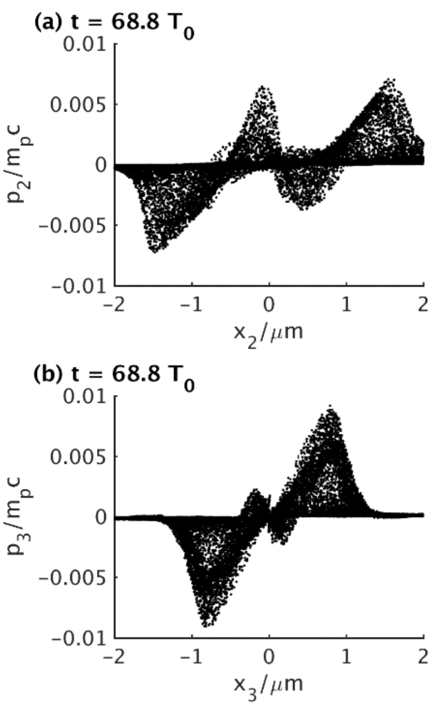

Figure 5: Proton distribution of transverse post-soliton in phase space of p_2x_2 (a) and p_3x_3 (b) at t = 68.8 T_0.

CONCLUSION

Electron and fields oscillations in a three-dimensional post-soliton electromagnetic field have been studied numerically by 3D-PIC simulations. We found that electron oscillation plays an important role in sustaining the stability of a post-soliton. Poloidal electric field and toroidal magnetic field also oscillate with electrons. Ions acceleration during cavity expansion is observed in such post-soliton structure.

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