SELF-INJECTION OF ELECTRONS FROM EVOLUTION OF WAKE WAVE

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Abstract

Self-injection mechanisms of plasma electrons in the self-modulated laser wakefield acceleration (SM-LWFA) are investigated. Two-dimensional (2-D) particle-in-cell (PIC) simulations show that a significant amount of plasma electrons can be self-injected into the acceleration phase of a laser wakefield by a dynamic increase of the wake wavelength in the longitudinal direction. In addition, a merging of the wake wave is observed and a large amount of electrons are self-injected to high energies. In this paper, injection phenomena are studied with 2-D simulations and a brief explanation of a new self-injection mechanism is presented.

INTRODUCTION

The laser wakefield acceleration (LWFA) has been highlightened since it is known that they can accelerate electrons to a relativistic high energy over a distance of the plasma wavelength λ_p [1]. For example, a maximum available electric field by the laser wakefield is on the order of 100 GV/m when a plasma density of $n_0 = 10^{18}\ \mathrm{cm}^{-3}$ is used. This electric field is three orders of magnitude stronger than that of conventional radio frequency (RF) accelerators. So far, various acceleration schemes have been studied, such as the plasma wakefield accelerator (PWFA) [2], the plasma beat wave accelerator (PBWA) [3, 4], the self-modulated laser wakefield accelerator (SM-LWFA) [5], and wakefield accelerators driven by multiple electron or laser pulses [6, 7].

Among those schemes, the SM-LWFA has been widely studied because of its simplicity. In the SM-LWFA, a long $(> \lambda_p)$ ultrahigh-intensity $(\geq 10^{18}\ \mathrm{W/cm^2})$ laser pulse is used to generate a laser wakefield in a homogeneous plasma. When the long laser pulse passes through the plasma, the laser pulse is modulated into many shorter pulses due to the Raman forward scattering instability. In this case, the modulated pulse width is equal to the plasma wavelength λ_p. These laser pulse train excites the wakefield resonantly and the amplitude of the wakefield grows up. The shape of the wakefield changes from a sinusoidal wave to a steep one as the wave grows, and eventually the transverse and the longitudinal wave breakings occur [8]. Due to this effect, some electrons are self-injected into the wakefield and they are accelerated to high energies. Some other effects are also known to be a source of the self-injection in the SM-LWFA and the beam quality of self-injected electrons are high enough to make an accelerator without any additional injection linac. Thus the SM-LWFA is considered as a strong candidate for the table top accelerator owing to its simple structure.

Even though the SM-LWFA has been deeply studied and great progresses has been made, large parts of the SM-LWFA study remains uncovered area. For example, various dynamical processes of wake wave evolution and electron self-injections can be observed in the simulation of the SM-LWFA. As mentioned previous paragraph, a laser pulse, which is longer than the plasma wavelength, is modulated to train of short laser pulses. The interaction continues until the modulated laser pulses get out of the plasma and the energy of the laser pulses shrink down as they pass through it so that the shape of the laser wake wave changes continuously. The self-focusing effect of the laser gives significant changes to the wake wave, as well. The transverse envelope oscillation of the laser after the self-focusing [9] increase or decrease the wavelength of the wake wave transversely. Moreover, during this process, a dynamic self-injection of electrons can be observed. During the evolution of the wake wave, it is noticed that there are sudden self-injections of electrons with dynamic changes of wake wave. These sudden electron injection is hard to be explained with previously known mechanisms of the SM-LWFA and it seems that there are a couple of other injection mechanisms. In this paper we describe the evolution of the wake wave and a dynamic self-injection of electrons. In addition, we propose a new mechanism of an electron self-injection which explains these dynamic self-injections of electrons.

SELF-INJECTION OF ELECTRONS BY EVOLUTION OF LASER WAKE WAVES

2-D PIC Simulation

As mentioned in the previous section, a laser wake wave changes dynamically in the longitudinal direction as it propagates in a plasma and this process leads to self-injection of some background plasma electrons in the laser wakefield. In order to investigate the longitudinal self-injection mechanism in SM-LWFAs, we performed 2-D PIC simulations with the OSIRIS code [10]. The OSIRIS code employs a moving window to simulate a laser plasma interaction with limited computing power. The moving

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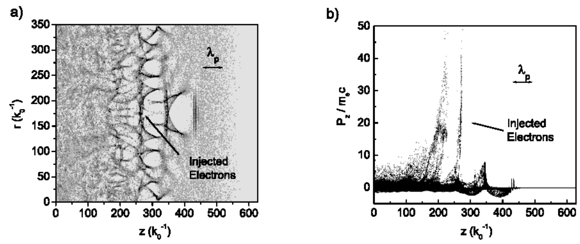

Figure 1: Electrons distribution of the plasma (a) and the phase space (b) when the laser propagates 0.76 mm (=6300ω_0^{-1}). The vector potential a_0 of the laser is 3.0 and the density of the plasma is 2×10^{19} cm^{-3}. The horizontal axis scale is $628k_0^{-1}$ $(= 80\ \mu\mathrm{m})$ and the vertical axis scale is $351k_0^{-1}$ $(= 45\ \mu\mathrm{m})$. The generated wake wave and self-injected electrons are shown. Note that the wavelength of wake wave is longer than the plasma wavelength λ_p.

window is on the frame of the laser pulse and advances with the speed of light. The electric and the magnetic fields are calculated only within the moving window. The values of fields are shifted by on mesh grid when the laser advances the distance $l > \Delta x$, where Δx is the grid size. Total simulation grid cell number is 1200×400 and 16 grid cells are used to resolve the laser wavelength. A periodic boundary condition is used for the r direction and the Lindman open-space boundary condition is used for the z direction. In the simulation, the plasma density is increased along the z axis from 0 to 2×10^{19} cm^{-3} over a distance of 0.25 mm, and then a homogeneous plasma density continues to the position of $z = 1$ mm. The plasma wavelength λ_p in the non-relativistic cold fluid regime is calculated to be 7.4 μm when the plasma density is 2×10^{19} cm^{-3}. The wavelength of the laser pulse is 1.064 μm and the pulse width is 40 μm (0.135 ps long), which is 5 times longer than the plasma wavelength λ_p. The direction of the laser is from left to right and the linear polarization is used. The laser pulse is focused in the plasma right after the plasma reaches its maximum density and the spot size at the focal point is 10 μm. The vector potential of the laser a_0 is 3.0 so that this simulation is in the relativistic self-focusing regime.

Self-Injection of Electrons

Figure 1 (a) shows the electron distribution when the laser propagates $6300\omega_0^{-1}$. The typical D shape of the wake wave and ion cavities are observed. Fig. 1 (b) is the phase space of Fig. 1 (a). Self-injected electrons are clearly seen and the bunch length of the electron beam is extremely short. Note that the wake wavelength (a distance between two electron peaks) is little longer than the plasma wavelength. As the laser propagates inside the plasma, it is observed that the wavelength of the wake wave is increased and electrons are self-injected simultaneously. Especially,

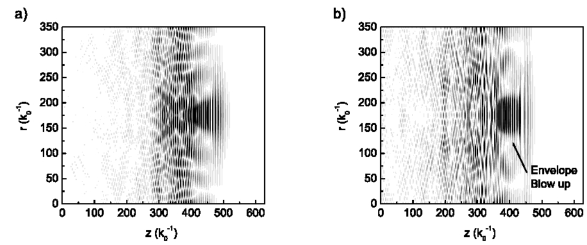

Figure 2: Transverse electric field at (a) $4200\omega_0^{-1}$, (b) $6300\omega_0^{-1}$ of Fig. 1 simulation. Note that there are a transverse oscillation of laser envelope and a serious longitudinal dispersion. These transverse oscillation and longitudinal dispersion can make an evolution of the wake wave.

the self-injection of electrons is enhanced as the longitudinal wavelength increases and it suddenly disappears when the wavelength shrinks down. In addition to the longitudinal development of the wavelength, the wake wave experiences the severe transverse modulation. The transverse size of the wake wave shrinks down straight forwardly until the laser pulse reaches its focal point and it shows a complex motion after the focal point. In one time the wake wave blows up and it is torn out into several pieces at the other time. From these longitudinal and transverse motion, the laser wake wave evolves dramatically and it seems that this evolution is closely related to the self-injection of electrons.

Mechanism of Electron Self-Injection

The wake wave evolution seems to be caused by two effects. One is the transverse oscillation of the self-focused laser pulse and the other is its dispersion in the longitudinal direction. Fig. 2 is the transverse electric field at different moving window positions. In the beginning (Fig. 2 (a)), laser pulses experience the self-focusing and the transverse size of the envelope is small. As the laser propagates into the plasma, the laser envelope blows up by the transverse oscillation of the self-focused laser pulse. The expanded transverse size of the laser pulse in Fig. 2 (b) is exactly matched with the wake wave in Fig. 1 (a) and it is clear that the transverse oscillation of the self-focused laser pulse causes the transverse modulation of the wake wave.

On the other hand, the longitudinal wavelength increase comes from the dispersion of the laser in which the group velocity of a laser pulse in a plasma is given by $v_g = c\sqrt{1 - \omega_p^2/\omega_0^2}$. In this equation, c is the velocity of light in free space, ω_p is the plasma oscillation frequency, and ω_0 is the laser oscillation frequency. This equation tells us that the laser pulse width increases when it passes through the plasma because the laser spreads its frequency spectrum by energy losing.

As a result of the transverse oscillation and the dispersion effect, the self-modulated short laser pulses change to

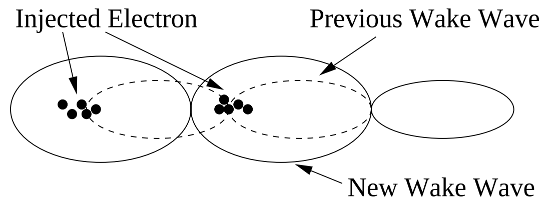

Figure 3: Schematic diagram of the electron self-injection mechanism. When the wavelength of the wake is increased, electrons in the previous nodes can be injected into the wakefield owing to their transverse momentum.

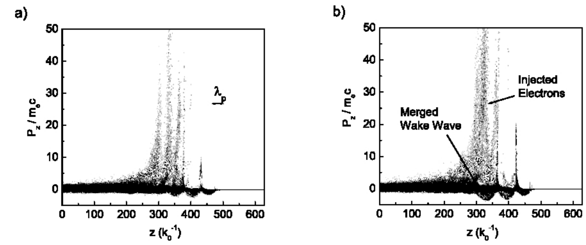

Figure 4: Phase space plot at (a) $2772\omega_0^{-1}$, (b) $3024\omega_0^{-1}$ when the vector potential is 2.0 and the density of the plasma is $5 \times 10^{19}\ \mathrm{cm}^{-3}$. Scales of the horizontal and the vertical axes are same with Fig. 1. Note that there is a merging of wake wave so that a large number of electrons are accelerated to high energies.

larger ones and this in turn increases the wake wavelength. When the laser envelop blows up, boundary electrons of the wake are pushed out so that the wavelength is increased and the strong self-injection of electrons occurs. This process can be explained in the schematic diagram in Fig. 3. When the evolution of the wake wave is happened, there is a mismatching between a previous wave and a new one so that most of electrons are pushed out to the new boundary. However, some electrons in previous nodes are injected into the acceleration phase of the wakfield owing to their strong transverse momentum. It should be noted that the increasing rate in λ_p is nonlinear. Hence, initial periods of the wake wave can be merged together (see Fig. 4) and this leads to a sudden self-injection of electrons as well.

Merging of Wake Wave

Fig. 4 is the phase space plot at different times of a simulation, which shows the merging of the wake wave. The density of the plasma is $5 \times 10^{19}\ \mathrm{cm}^{-3}$ and the vector potential a_0 is 2.0. At first, it starts from a typical phase diagram of the SM-LWFA. The wavelength of the wake wave is given by the plasma wavelength λ_p, even though wavelengths of first two periods are longer than that. As the laser propagates into the plasma, dramatic changes are observed (see Fig. 4 (b)). A large amount of electrons are injected strongly into the wakefield and accelerated to high energies. The wavelength of the third period is increased 2 times longer than the plasma wavelength λ_p and this means that two wake periods is merged into one. The merging of the wake wave is also confirmed with the expanded boundary of the wake wave. Below the zero momentum, the boundary of the wake wave blows up two times bigger than before.

SUMMARY

PIC simulation studies have been performed to investigate the self-injection mechanisms in the SM-LWFA. These studies show that a significant amount of plasma electrons can be self-injected into a wakefield when the laser wake wave evolves dynamically in the longitudinal direction. The transverse oscillation and the longitudinal dispersion of the laser envelope cause this evolution of wake wave. This injection is so severe that it seems to be a dominant self-injection source in some cases. In addition to the increase of longitudinal wavelength, the merging of two period is observed and this merging causes the self-injection of a large number of electrons as well.

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