ELECTRON ACCELERATION BY LASER WAKEFIELDS IN TAPERED PLASMA DENSITIES

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Abstract

When a laser wake wave passes through a sharp downward density transition in plasmas, a significant amount of plasma electrons are self-injected into the acceleration phase of the wakefield and accelerated to relativistic high energies over a very short distance. We report that the energies of the injected plasma electrons can be increased a few times if an upward density tapering is used. Although space-charge effect of the trapped electrons deforms the accelerating wakefield severely, it is demonstrated that density tapering is a very effective way to enhance the trapped electron energies.

INTRODUCTION

Laser and plasma-based acceleration methods[1] can provide very high acceleration gradients on the order of 100 GeV/m. So far various acceleration methods based on different injection schemes[2-5] have been investigated. One of them is the self-injection and acceleration method of background plasma electrons at a sharp downward density transition.[5] Originally this self-injection method was devised for an electron-beam-driven plasma wakefield acceleration (PWFA), but we found that a superficially similar self-injection and acceleration phenomenon could happen for a laser-driven wakefield acceleration (LWFA).

In the case of using a short intense laser pulse, however, there are some differences from that of using a high-energy electron beam pulse. One of them is that the group velocity v_g of a laser pulse in a plasma is significantly smaller than that of an ultrarelativistic electron beam pulse as $v_g = c(1-\omega_p^2/\omega_0^2)^{1/2} < c$. Here, c is the velocity of light in free space, ω_p and ω_0 are the plasma oscillation frequency and laser frequency, respectively. Since the phase velocity v_{ph} of a laser wakefield is almost equal to v_g, v_{ph} becomes smaller than the accelerated electron speed in the highly relativistic regime. Hence, the trapped electrons and the laser wakefield become out of phase as the trapped electrons are accelerated to highly relativistic energies. This phase slippage effect limits the maximum available electron energy before the diffraction effect of a drive laser pulse is significant. Calculation of Sprangle *et al.*[6] showed that an externally-injected single test particle can gain a significantly higher energy when it is placed in a density-tapered plasma channel. In their calculation, however, the space-charge effect was not taken into accounted as only a single test particle was used. In their case, furthermore, the diffraction effect of a drive laser pulse was cancelled by a focusing effect in a preformed parabolic plasma channel so that only 1-dimension-like treatments were done. In this paper, we report 2-D simulation results, in which trapped plasma electrons by the self-injected laser wakefield acceleration using a sharp density transition can gain significantly higher energies when the trapped particles are accelerated in a tapered plasma density.

SIMULATION RESULTS

In order to investigate the energy enhancement effect of the trapped plasma electrons in the self-injected laser wakefield acceleration, we performed 2-D particle-in-cell (PIC) simulations as a satisfactory 2-D theory does not exist yet. For this purpose, we used the fully relativistic and electromagnetic OSIRIS code[7] that employs a moving simulation window. Two different cases shown in Fig. 1 were simulated, in which one (Case-I) is without density tapering and the other (Case-II) has upward density tapering. In both cases, the plasma densities have $n_0 = 5\times10^{18}$ cm^{-3} and $n_0^{II} = 0.6 n_0^{I}$, respectively, and n_0^{III} in Case-II is varied to change the tapering slope. Here, the superscripts II and III denote parameters for n_0^{II} and n_0^{III}, respectively. In the simulations, the laser pulse length L is slightly smaller than λ_p^{II}, the plasma and laser frequency ratio ω_p^{II}/ω_0 is 0.04, and the normalized vector potential a_0 defined by $a_0 = p_0/m_e c$ is 2.5 at the laser beam waist. Here, p_0 is the electron oscillation momentum due to the laser electric field and m_e is the electron rest mass. For the given laser and plasma parameters, simulations have been

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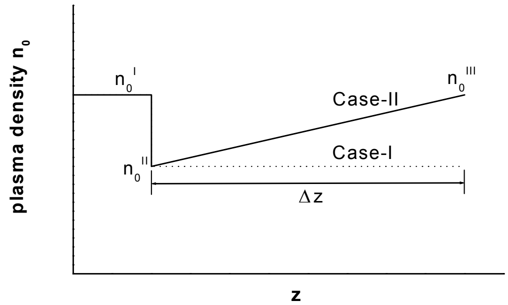

Figure 1: Plasma density profiles for untapered and tapered cases.

performed with $n_0^{II} = n_0^{III} = 0.6 n_0^{I}$ in Case-I and the result is shown in Fig. 2. Figure 2 illustrates the trapping and acceleration phenomenon by the self-injected laser wakefield acceleration. In this simulation, the laser beam is focused to a minimum diameter of 19 μm around the sharp downward density transition (shown as a vertical line in the top figure of (a)), and then the laser beam size increases due to diffraction as it propagates in the plasma. When the laser wake wave passes the density transition, λ_p increases suddenly so that some background plasma electrons are self-injected into the acceleration phase of the first period of the laser wake wave (see the top figure of (a)). The injected plasma electrons are trapped by the wakefield and accelerated to high energies, as shown in Fig. 2(b). As mentioned above, however, the accelerated particles outrun the laser wakefield, which is evidently shown in the bottom figure of Fig. 2(a). As a result, the particles eventually arrive in the deceleration phase of the wakefield and can not gain energy any more.

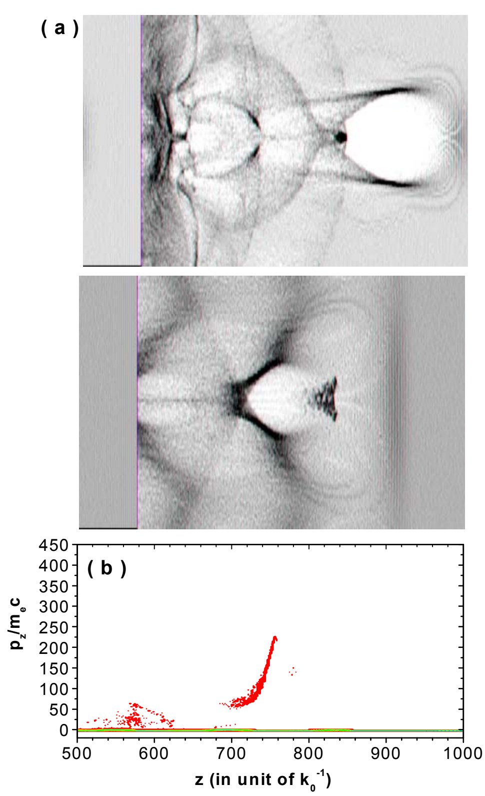

Figure 2: Simulation results for the untapered density profile (Case-I): (a) phase space plots (*y,z*) of plasma electrons at two different positions (the distance is $8421\, k_0^{-1}$) and (b) momentum phase space plot (p_z, z) for the bottom in Fig. 2(a).

Energy saturation of the self-injected particles due to the detuning effect may be overcome by using upward density tapering. To investigate the tapering effect, a linearly tapered density (Case-II in Fig. 1) was used in simulations, in which the density increases from $n_0^{II} = 0.6 n_0^{I}$ to $n_0^{III} = 1.3 n_0^{II}$ over a distance of $\Delta z = 9300 k_0^{-1}$. Here, k_0 is the wavenumber of laser light in free space. In this case, the simulation result indicates that the laser wakefield wavelength decreases gradually as the wake wave propagates along the upward density tapering, so the trapped particles stay in the acceleration phase over a longer propagation distance, compared to the untapered case. In other words, the initial phase velocity v_{ph}^{II} of the first node in the wake wave is gradually increased to $v_{ph}^{III} \cong v_{ph}^{II} + (\lambda_p^{II} - \lambda_{III}) / \Delta t > v_{ph}^{II}$, where Δt is the time that is taken for the wake wave to propagate the distance Δz. Due to the increased phase velocity of the wakefield, therefore, the detuning effect can be reduced. Of course, it should be pointed that the increased density leads to a smaller v_g, but this effect is minor as $v_g \cong c$ for $\omega_p / \omega_0 << 1$. Instead, the increasing v_{ph} effect is much more significant as $\lambda_p^{III} / \lambda_p^{II} = (n_0^{II} / n_0^{III})^{1/2}$. Comparison of Fig. 3(a) and Fig. 2(a) clearly shows the reduction in detuning (slippage). As a result, significantly higher energies for the trapped plasma electrons can be produced, as shown in Fig. 3(c). However, it should be pointed out that the self-injected plasma electrons deform the laser wakefield severely, which leads to deterioration and reduction of the accelerating wakefield. This results from the strong space-charge effect of the tightly focused {\it plasma electron beam}, in which the focusing force is provided by the background ions and remnant electrons in the wake wave. The superstrong radial focusing force is given by

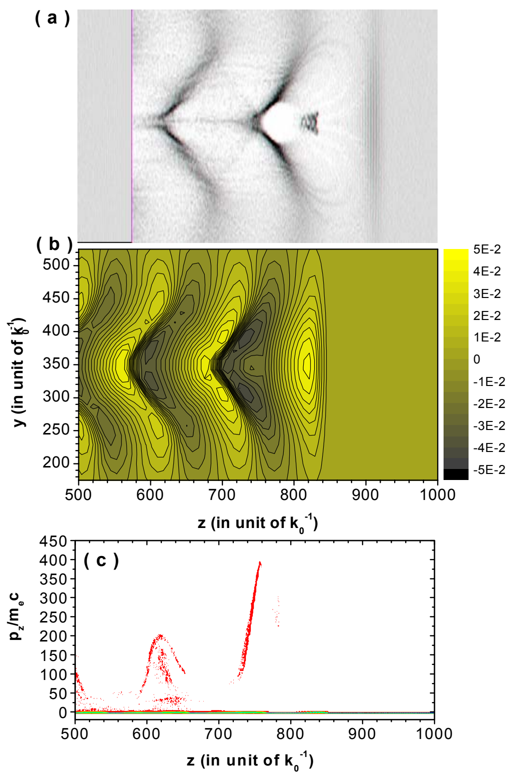

Figure 3: Simulation results for the upward density tapering (Case-II) : (a) phase space plot (*y,z*) of the plasma electrons, (b) longitudinal electric field E_z in the plasma, and (c) momentum phase space (p_z, z) of the plasma electron.

$F_r = (n_0 - \Delta n_0)e^2 r / 2\varepsilon_0$, where Δn_0 is the remnant electron density in the wake wave, *r* is the radial distance from the axis, and ε_0 is the permittivity of free space. Due to the strong focusing, the plasma electron beam density n_b is larger than the background plasma density so that the beam space-charge force expels almost all ambient plasma electrons transversely and generates another small plasma wake wave behind the beam, as shown in Fig. 3(a) (note that an electron-free ion cavity is produced behind the beam).

In the tapering case, degree of slippage is dependent on the upward density gradient. Figure 4 shows comparison of two tapered cases and untapered case. It shows that tapered cases increase the detuning distance noticeably and higher energies can be achieved. Figure 3 implies that there is more room for energy enhancement with density tapering. Hence, it is expected that higher energies can be obtained if steeper density gradients are used.

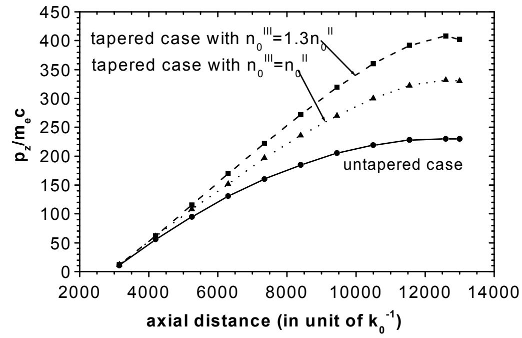

Figure 4: Comparison of momentum gains for untapered and tapered cases.

SUMMARY

It was demonstrated that electron energies by the self-injected laser wakefield acceleration can be enhanced a few times by using an upward density tapering in 2-D cases. Although space-charge force of the self-injected plasma electrons deforms the wakefield severely, the electron energies can be increased effectively before the diffraction effect of a laser pulse eventually limits the energy gain. This kind of self-injection and energy enhancement scheme with a density tapering may be demonstrated with a special-shaped gas jet in relatively low densities (e.g. $n_0 = 10^{16} \sim 10^{17}$ cm^{-3}).

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