SIMULATIONS OF PHOTON ACCELERATION AND LASER PULSE AMPLIFICATION USING LASER PLASMA INTERACTIONS

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Abstract

Two simulation studies of laser-plasma interactions are presented. In photon acceleration study, we present the interaction of a short laser pulse with a negative density gradient of a relativistic electron plasma wave generated by a drive laser pulse. The effects of slippage, dispersion, and diffraction are discussed. In order to make a strong plasma wake field, an ultrashort high-intensity laser pulse is necessary. We present laser pulse amplification and compression through stimulated Raman backscattering via the interaction with a plasma and a counter-propagating pump laser. With a one-dimensional fluid model, nonlinear growth rate, pulse compression rate, and energy transfer efficiency are investigated for various parameters to optimize the amplification.

1 PHOTON ACCELERATION

Although the speed of light is constant in vacuum, it is possible to increase or decrease the speed, thus the energy, of photons by using a medium which has nonuniform index of refraction. When a laser pulse is located on a downward density gradient of a plasma wave, the frequency of the laser pulse is upshifted and the group velocity increases. This phenomenon is called photon acceleration [1]. The interaction length between the laser pulse and the density gradient can be extended significantly by using a wake field generated by a short laser pulse.

A probe pulse is launched with a time delay following a high intensity drive pulse propagating through a plasma. Because the interaction is most effective when the group velocity of the probe pulse is same as the phase velocity of the plasma wave generated by the drive pulse, the frequency of the probe and the drive pulses are set to be same, as ω_0. The plasma density is assumed to be uniform as n_0 with a plasma frequency ω_{p0}. The wavelength of the plasma wave is $\lambda_{p0} = 2\pi c/\omega_{p0}$, where c is the speed of light. When the driven plasma motion is not highly relativistic, the density perturbation δn is linearly proportional to the drive pulse intensity and shows a sinusoidal shape as

$$\delta n(\zeta) = \delta n_0 \sin(k_{p0}\zeta), \qquad (1)$$

where $\zeta = k_0 z - \omega_0 t$, $k_0 = (\omega_0^2 - \omega_{p0}^2)^{1/2}/c$, and $k_{p0} = 2\pi/\lambda_{p0}$. From the dispersion relation of electromagnetic waves propagating through plasmas, the maximum frequency shift is calculated as [2]

$$\frac{\Delta\omega}{\omega_0} = \pi \frac{\omega_{p0}^2}{\omega_0^2}\frac{\delta n_0}{n_0}\frac{v_g\tau}{\lambda_{p0}}, \qquad (2)$$

where v_g and τ are the group velocity of the probe pulse and the propagation time, respectively. With this mechanism, it is possible to vary the laser wavelength continuously within the frequency upshift limit by changing the interaction length, $v_g\tau$.

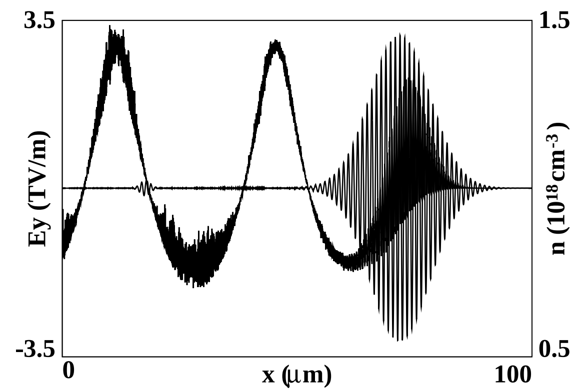

Figure 1: One-dimensional diagram of photon acceleration. Shown are the profiles of electron density (dark line) and propagating laser pulses.

In this study, we present simulation results of photon acceleration by one-dimensional (1d) electromagnetic particle-in-cell (PIC) codes, 1d-XOOPIC [3]. Figure 1 shows a one-dimensional (1d) schematic diagram of photon acceleration. The drive pulse with a FWHM of 50 fs generates plasma wake fields of which wavelength is $\lambda_{p0} = 33$ μm for the plasma density $n_0 = 10^{18}$ cm^{-3}. The normalized vector potential of the drive pulse is $a_0 \equiv eE_y/mc\omega_0 = 1.0$, which corresponds to a laser intensity of 1.18×10^{18} W/cm^2 for the used wavelength, $\lambda = 1$ μm. It induces 40% of electron density perturbation. The probe pulse with a FWHM of 8.2 fs is launched with a time delay so that it should be located at the place where the density gradient is negative, around 20 μm in Fig. 1. The time delay, τ_d, is associated with the plasma wavelength of the wake field, as $\tau_d \simeq 1.75\lambda_{p0}/c$. In order to generate plasma wake field, the drive pulse intensity should be very high,

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but the probe pulse intensity needs to be small enough that the electric field should be lower than the wave breaking limit, $mc\omega_{p0}/e$. Both drive and probe pulses are shown in a moving window propagating to the right with the speed of light.

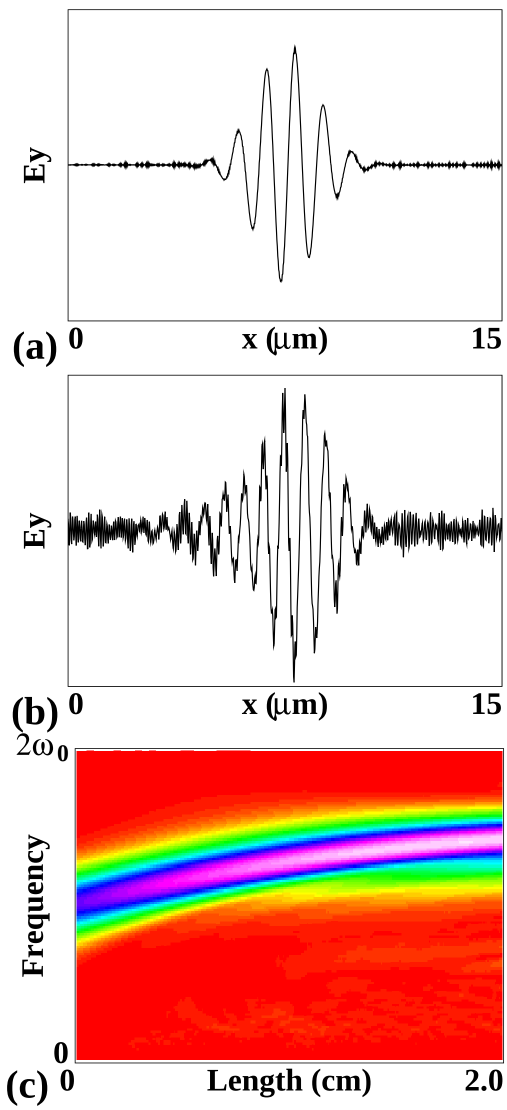

Figure 2: One-dimensional simulation results : (a) the pulse shape at the initial time, (b) the pulse shape when the interaction length is 2 cm, and (c) contour plot of frequency vs. interaction length.

Figure 2 shows a 1d simulation result in which about 40% of frequency upshift was observed after 2.0 cm of interaction length. The used parameters are described in Fig. 2. Moreover, 150% of frequency upshift was observed with an increased intensity of the drive pulse, $a_0 = 2.0$. In 1d simulation, however, diffraction of the laser pulses is not considered and thus the interaction length is much longer than that of real situation. In two-dimensional (2d) simulation with OSIRIS code [4], it was observed that photon acceleration saturates at smaller interaction length with only 10% of frequency upshift because of laser pulse diffraction and the transverse plasma motion.

Diffraction, wave dispersion, drive pulse depletion, and dephasing between the probe pulse and the plasma wake field play important roles in the saturation of photon acceleration. As can be seen in Eq. (2), the frequency upshift is more effective for higher n_0 and a_0, but the plasma density and the laser intensity of the drive pulse cannot be increased arbitrarily because strong wave dispersion happens especially when the pulse length of the probe pulse is short. $\Delta\omega$ increases as the plasma density increases, but the plasma wavelength decreases and therefore the probe pulse becomes more dispersive when the pulse length of the probe pulse is comparable to a half of the plasma wavelength. For this case, the center of the probe pulse has faster group velocity than the front or the tail of the pulse. Moreover, if the pulse length is longer than a half of the plasma wavelength, frequency downshift also can happen at positions where density gradient is positive. $\Delta\omega$ also increases as we increase the drive pulse intensity, a_0, but the density gradient becomes sharp and appears within a narrow region, which also makes the pulse more dispersive. Moreover, if we decrease the laser spot size to increase the intensity of the drive pulse, the Rayleigh length decreases and the interaction length becomes shortened by diffraction.

The interaction length, $v_g\tau$, is restricted to a few Rayleigh lengths by diffraction, and also restricted by the drive pulse depletion which gives its energy to plasma wake fields. The energy depletion is proportional to the interaction length, a_0^2, and ω_{p0}^2/ω_0^2. Diffraction can be controlled by optical guiding of the laser using plasma channels. As the group velocity of the probe pulse increases by photon acceleration, the difference increases between the group velocity of the probe pulse and the phase velocity of the wake field. As the probe pulse is accelerated, it deviates from the acceleration phase. Dephasing can be controlled by changing the plasma density gradually as the pulse propagates.

2 LASER PULSE AMPLIFICATION

It is necessary to generate an ultrahigh intensity (more than 10^{18} W/cm^2) sub-picosecond laser pulse for the applications to the laser wake field accelerator (LWFA) or inertial confinement fusion (ICF). For the achievement of high laser power, the chirped pulse amplification (CPA) technique [5] is widely used, but the gratings needed to stretch and compress the laser pulses will become quite large and expensive for the laser power about kJ per each pulse. For this reason, it is natural to exploit other methods to amplify a high-intensity short laser pulse. Recently, it was reported that the three wave interaction between counter-propagating electromagnetic waves and a plasma wave can generate superradiant amplification of a short laser pulse [6, 7], and verified with 1d and 2d electromagnetic PIC simulations [3, 8].

In this study, we investigated the characteristics of the laser amplification using stimulated Raman backscattering. For fast simulation, a 1d fluid model was developed for the envelope equations with assumption of $\omega_1 \gg \omega_p$:

$$\frac{\partial f}{\partial t} + i\delta\omega f = -\frac{c}{4}k_f a_1^* a_0, \quad (3)$$

$$\frac{\partial a_1}{\partial t} + v_{g,1}\frac{\partial a_1}{\partial x} = -\frac{c}{4}k_f \frac{\omega_p}{\omega_1} a_0 f^*, \quad (4)$$

$$\frac{\partial a_0}{\partial t} - v_{g,0}\frac{\partial a_0}{\partial x} = \frac{c}{4}k_f \frac{\omega_p}{\omega_0} a_1 f, \quad (5)$$

where $f = eE_x/mc\omega_p$ is the normalized electric field of the plasma wave with electron plasma frequency ω_p, a_s and ω_s are the normalized vector potential and the frequency, with indices $s = 0$ and 1 which mean the pump and the seed pulses propagating to the left and to the right respectively, $k_f = k_1 + k_0$ is the sum of the wavenumbers, $\delta\omega = \omega_0 - \omega_1 - \omega_p$, and $v_{g,s} = c^2 k_s/\omega_s$ is the group velocity of each pulse. The amplification is maximized when the three waves satisfy the matching condition of Raman backscattering, $\omega_0 = \omega_1 + \omega_p$.

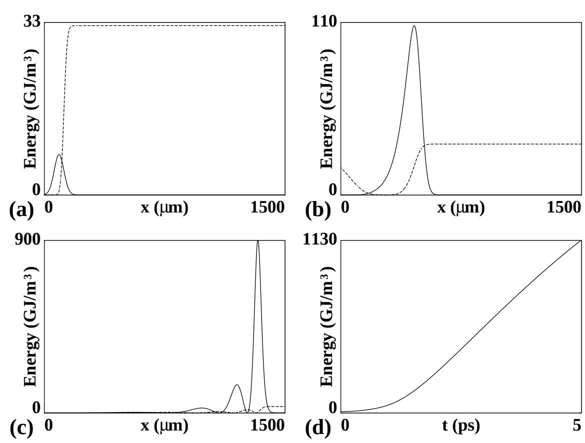

Figure 3: Simulation of laser pulse amplification with initial quantities of $a_0 = 0.01$, $a_1 = 0.005$, and $\omega_p/\omega_1 = 0.02$. Shown are the energy densities of the seed (solid) and the pump (dashed) at (a) $t = 0$, (b) $t = 1.35$ ps, and (c) $t = 4.1$ ps, and (d) the time evolution of peak energy density.

Figure 3 shows the simulation results of the seed pulse amplification. For the case, the seed pulse energy has been amplified more than 150 times during 5 ps and the pulse width has been compressed almost by half.

In the linear regime where $\omega_B \equiv 2\omega_1\sqrt{a_0 a_1} < \omega_p$, the peak intensity of the seed pulse increases exponentially as shown in Fig. 3(d) for $t < 1.3$ ps. The growth rate is calculated by linearizing Eqs. (3)-(5), as $\gamma = 0.5a_0\sqrt{\omega_1\omega_p}$. In the linear regime, the front and the peak of the seed pulse propagate with different velocity [7], and thus pulse broadening happens as shown in Fig. 3(b). After the seed pulse has been amplified enough, 100% of pump depletion occurs [Fig. 3(b)] and $\omega_B > \omega_p$ (nonlinear regime). The energy growth is not exponential any more but increases with t^β relation, where β was observed to be 1 over all parameters. Contrary to the linear regime, the pulse is compressed in the nonlinear regime because the rear part of the seed pulse cannot be supplied with energy by the fully depleted pump. Moreover, the rear part give its energy to the pump by three wave interaction so that the restored pump amplifies the seed behind the main peak again, and thus subsidiary pulses are generated as shown in Fig. 3(c). By this process, the energy of the rear part of the first pulse is transferred to the subsidiary pulses and the first pulse becomes compressed. Therefore, pulse compression time scale is strongly related to the generation of the subsidiary pulses. However, the first pulse has more than 80% of the total energy of the seed, and the peak energy of the first pulse does not saturate in 1d model despite the generation of subsidiary pulses because it gains energy from the unperturbed counter-propagating pump.

3 SUMMARY

Simulations of photon acceleration using plasma wake fields and laser pulse amplification using Raman backscattering have been presented with electromagnetic PIC simulation codes, 1d-XOOPIC [3] and 2d OSIRIS [4].

In the photon acceleration simulation, up to 150% of frequency upshift was observed after 2 cm of pulse propagation in 1d simulation, but only 10% for 2d simulation because of short interaction length limited by laser diffraction and transverse plasma motion. Saturation mechanisms such as diffraction, dispersion, pump depletion, and slippage are discussed.

In the simulation of laser pulse amplification, a 1d fluid model was developed for the slowly varying envelope equations to investigate the amplification characteristics. The seed pulse is amplified exponentially with the growth rate of $\gamma = 0.5a_0\sqrt{\omega_1\omega_p}$ in linear regime, and proportionally to t^1 in nonlinear regime. The pulse compression rate is associated with the pump depletion and the generation of the subsidiary pulses.

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