Rapid Communications

Acceleration of Injected Electron Beam by Ultra-Intense Laser Pulses with Phase Disturbances

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Acceleration of an injected electron beam by ultra-intense laser pulses with phase disturbances is investigated. The energy gain of the beam electrons depends on the initial energy of the injected electrons in the stochastic acceleration process. The effect is larger for electrons with some injection energy as opposed to electrons with no initial energy. The corresponding accelerating field for electrons having certain amounts of initial energy becomes larger than that of the standard wakefield.

Keywords:
ultra-intense laser, electron beam acceleration, stochastic acceleration

Plasma-based accelerators have attracted great attention since the idea was proposed by Tajima and Dawson in 1979 [1]. Intense laser pulses excite the plasma wave in different ways, such as by the laser wakefield, laser beat wave, and self-modulated laser wakefield [2]. The acceleration of the injected electron beam in plasma-based accelerators has also attracted attentions and highly accelerated electrons have been observed in recent experiments of the laser wakefield scheme [3,4]. In an experiment [4], over 100 MeV acceleration gain was obtained, where the accelerating field is estimated as 10 GeV/m and the acceleration length as 1 cm which seems to be difficult to achieve without self-channeling since it is much longer than the Rayleigh length [5]. On the other hand, Multi-MeV electrons of which energy seems to be higher than expected based on the wakefield acceleration, are observed due to the direct laser acceleration mechanism for a moderate density plasmas ($n_e \gtrsim 0.1 n_c$, where n_e and n_c are the plasma and critical density, respectively.) [6,7].

A mechanism of the stochastic acceleration for background electrons by ultra-intense lasers with phase disturbances has been proposed [8,9], where its accelerating field is higher in amplitude than that of the wakefield, and the acceleration length is not limited by dephasing since coherent interaction such as the wakefield is not demanded. The stochastic acceleration mechanism becomes dominant when the intense laser pulse has stochastic phase disturbances [9] or is in the presence of a stochastic field [8]. An intense laser pulse might be disturbed by the nonlinear interaction of the intense laser field with dispersive medium, such as dense gases and moderate density plasmas [10].

In this paper, we investigate an injected electron beam accelerated by the stochastic acceleration mechanism which gives more effective acceleration of beam electrons [9]. Briefly, the model of the stochastic acceleration is shown here. We have modeled the laser-plasma interaction as follows. The laser pulse is modeled as a composition of plane electromagnetic fields. The electrons move into a neighboring filament with finite time step τ_c in the acceleration process. The phase of the electromagnetic field ϕ in each filament is assumed to be randomly different. The electrons distribution function is then described by the Fokker-

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Planck equation

$$\frac{\partial f_e}{\partial \eta} = \frac{a^2 D}{2\tau_c^2}\left(\frac{\partial^2 f_e}{\partial u_x^2} - 3\frac{\partial}{\partial u_z}\frac{f_e}{\alpha} + u_x^2\frac{\partial^2}{\partial u_z^2}\frac{f_e}{\alpha^2}\right),$$

where u_x and u_z are normalized momentums transverse to and parallel to the laser wave vector, η is time normalized with laser frequency, $\alpha = \sqrt{1+u_x^2+u_z^2} - u_z$, and D expresses the time correlation of laser phase, *i.e.*, $< \phi(\eta)\phi(\eta') > = D\delta(\eta - \eta')$ where $D \ll 1$. The coefficient D may depend on the experimental condition. The experimental result [7] is well explained by the Fokker-Planck equation with D = 0.07 and the acceleration of background plasma electrons. The details of the analytical model and its characteristics can be found in Ref. [9].

The acceleration of the injected electron beam by stochastic acceleration is estimated with the parameters $a = 3.0$, $\tau_c = 10$, and $D = 0.07$, which correspond to the analysis of the experimental conditions [7]; $P = 1.2$ TW, $\lambda = 0.8$ μm, and $n_e = 2 \times 10^{20}$ cm^{-3}. The initial distribution is a shifted Maxwellian with an average energy of 20 MeV. The energy spectrums are plotted in Fig. 1. It is shown that most electrons are accelerated and have acquired very high energy, which is greater than 100 eV, but a small portion of electrons are decelerated (still $u_z \geq 0$). In Fig. 2, the acquired energy is plotted as a function of the initial beam energy at ωt = 1,000 which corresponds to a channel length of 112 μm. The acquired energy, G, is defined as $G \equiv U_{\mathrm{kin}}(t) - U_0$, where U_0 is the average of the initial kinetic energy of injected electrons. The kinetic energy, $U_{\mathrm{kin}}(t)$, is defined as

$$\frac{1}{N}\int_{U_{\mathrm{kin}}(t)}^{\infty} f_e(U)\,\mathrm{d}U = 10^{-6},$$

where N is the total number of the electrons. The effective accelerating field, E_a, which is defined as the acquired energy divided by the acceleration or interaction length is shown on the right-hand ordinate in Fig. 2. The accelerating field becomes quite large for beam electrons, *e.g.*, $E_a \simeq 950$ GV/m for the initial beam energy of 40 MeV. This amplitude is comparable to the wave breaking limit of the plasma wave when $n_e/n_c \simeq 0.1$. For the standard laser wakefield acceleration, the laser parameters corresponding to the field become 3 fs in duration and $a = 2$, which is quite a high requirement.

In conclusion, stochastic acceleration becomes effective for beam electrons interacting with an ultra-intense laser ($a \geq 1$) with phase distrubances, and whose initial energy is higher than about a few MeV. The injected electrons acquire such high energy (> 100 MeV) when the interaction length is only of the order of a hundred microns, which is the Rayleigh length in typical experiments. The details of the beam quality or the angular spectrum of the high energy electron will be investigated further in the future.

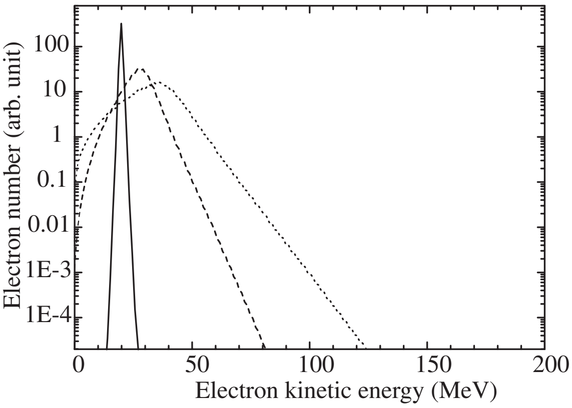

Fig. 1 Normalized electron energy spectra for a case where $a = 3.0$, $\tau_c = 10$, $D = 0.07$. The solid, dashed, and dotted lines are at ωt = 50, 1,000, and 2,000, respectively.

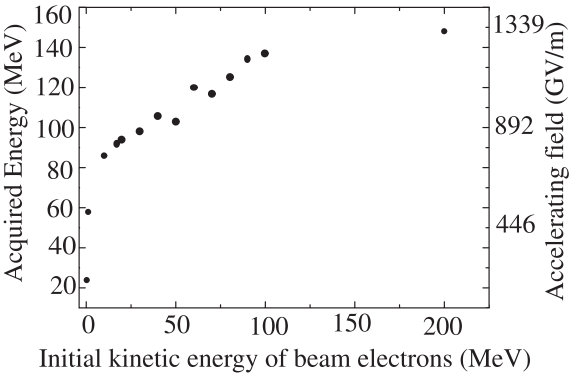

Fig. 2 Acquired energy and effective accelerating field v.s. initial kinetic energy of electron beams.

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