Forward acceleration and generation of femtosecond, megaelectronvolt electron beams by an ultrafast intense laser pulse

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We present a new mechanism of energy gain of electrons accelerated by a laser pulse. It is shown that when the intensity of an ultrafast intense laser pulse decreases rapidly along the direction of propagation, electrons leaving the pulse experience an action of ponderomotive deceleration at the descending part of a lower-intensity laser field than acceleration at the ascending part of a high-intensity field, thus gain net energy from the pulse and move directly forward. By means of such a mechanism, a megaelectronvolt electron beam with a bunch length shorter than 100 fs could be realized with an ultrafast ($\lesssim$ 30 fs), intense ($> 10^{19}$ W/cm^2) laser pulse.

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The development of high-intensity lasers has made it possible to study extreme physics on a tabletop[1]. An important issue of the high-intensity interactions is the generation of high-brightness, megaelectronvolt (MeV) electron beams at relativistic laser intensities ($> 10^{18}$ W/cm^2), which is not only of fundamental interest in relativistic interactions, but also can be applied to the fast ignition of inertial confinement fusion, X-ray and γ-ray generation, and compact particle acceleration, etc[2-4].

MeV electron beams have been observed via plasma wave acceleration, wavebreaking, ponderomotive laser acceleration, stochastic heating, and so on[5]. But the extraction of net energy of the accelerated electrons from the high-intensity laser-matter interactions has not been fully understood yet. This paper is to provide new understanding of electron acceleration in the longitudinal or in the laser pulse's propagating direction[6], and based on this, a new mechanism of energy gain of the accelerated electrons is proposed. We will show that when the field intensity of an ultrafast relativistic-intensity laser pulse decreases rapidly along the direction of propagation, some electrons which are initially at rest experience ponderomotive deceleration at the descending part of the laser pulse with a lower intensity than acceleration at the ascending part of the laser pulse. As a result, after the laser pulse traverses them, the electrons can gain net energy from the pulse and move directly forward. It differs from the previously discussed ponderomotive laser acceleration in which the transverse component of the ponderomotive force or the transverse gradient of the laser field had to be included for net energy gain of the accelerated electrons[7-11]. The present mechanism may be applied to the generation of an ultrashort electron beam, by either laser-gas or laser-solid interactions. It will also be helpful to elucidate the anomalous laser absorption by accelerated electrons in high-intensity interactions.

In the following, we will use test particles for further analyses. To describe the field intensity decrease of a laser pulse along the direction of propagation, we introduce an attenuation coefficient for the laser field. Such a model may apply to several situations, as will be discussed later. The laser field is linearly polarized and the normalized vector potential is assumed to be

$$\mathbf{a} = a_0 \cdot \sin^2\left(\frac{z-ct}{c\tau}\right) \cdot \sin(\omega t - kz) \cdot \mathrm{e}^{-\alpha(z-z_0)}\hat{x}$$
$$(z < z_0, \alpha = 0; z \geq z_0, \alpha > 0), \quad (1)$$

in which a_0 is the amplitude of the normalized vector potential or the laser strength parameter, α is the attenuation coefficient, ω, k, c are the angular frequency, the wave vector, and the velocity of the light, respectively. The laser pulse has a sine-square temporal profile, and its pulsewidth is 1.14τ in full width at half maximum (FWHM). The vector potential $\mathbf{A}$ is related to $\mathbf{a}$ by $\mathbf{A} \equiv (mc/e)\mathbf{a}$, in which m and e are the electron's mass and charge, separately. Following the expression of $\mathbf{A}$, the Coulomb gauge is satisfied that $\nabla \cdot \mathbf{A} = 0$. The electric field $\mathbf{E}$ and the magnetic field $\mathbf{B}$ of the laser pulse are calculated with the Maxwell equations

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}, \quad \mathbf{B} = \nabla \times \mathbf{A}. \quad (2)$$

An electron's motion under the laser's electromagnetic field is governed by relativistic motion equations

$$\frac{\mathrm{d}(\gamma m \mathbf{V})}{\mathrm{d}t} = (-e)(\mathbf{E} + \mathbf{V} \times \mathbf{B}), \quad (3)$$

$$\frac{\mathrm{d}(\gamma m c^2)}{\mathrm{d}t} = (-e)\mathbf{E} \cdot \mathbf{V}, \quad (4)$$

where $\mathbf{V}$ is the electron's velocity and γ is the relativistic factor, given by $\gamma = 1/\sqrt{1 - V^2/c^2}$. Insert $\mathbf{E}$ and $\mathbf{B}$ into Eqs. (3) and (4), and solve the two equations and the following equation numerically,

$$\frac{\mathrm{d}\mathbf{R}}{\mathrm{d}t} = \mathbf{V}, \quad (5)$$

where $\mathbf{R}$ denotes the electron's position vector. Thus we can obtain the electron's trajectory, momentum, and kinetic energy, separately. Suppose the interaction region ranges from $z = 0$ to 100 μm, in which there exist free electrons that are at rest before the laser pulse arrives.

The laser pulse with central wavelength of 800 nm propagates with a constant peak-intensity along the z-axis from the outside into this region, and at the position $z = z_0 = 50$ μm the laser-field intensity begins to decrease.

A typical result is shown in Fig. 1, which gives the final velocities of electrons, initially located at different positions along the z-axis, after the laser pulse traverses them for different a_0. It shows that when starting from some position, the intensity of the laser pulse decreases significantly in a short distance, some electrons, accelerated by the laser field can gain net energy after the pulse overtakes them. Recall from Eq. (1) that the laser's electromagnetic field is uniform in the direction perpendicular to the laser's propagation direction, there is no gradient of the laser field in the transverse direction. It is also found from the calculations that these net-energy-gain electrons are emitted directly forward along the direction of the laser pulse's propagation.

Figure 1 also shows that only the electrons initially in a limited region can gain net energy after the laser pulse overtakes them. Outside this region electrons cannot gain net energy. The detailed dynamics can be understood from Fig. 2, which gives a comparison of the relativistic factor, γ, as a function of their longitudinal positions z for two representative electrons initially located at two different positions. One, initially located at $z_i = 21$ μm, represents electrons which cannot gain net energy after the laser pulse traverses them. The other, initially located at $z_i = 42$ μm, represents electrons which can gain net energy. For the first electron (without energy gain), it experiences the well-known two equal-amount but opposite processes of acceleration and deceleration[12,13]. At the ascending-part of the laser pulse, the electron is accelerated and obtains kinetic energy from the laser field. At the descending-part of the pulse, it is decelerated and returns an equal amount of the energy to the laser field. So the electron obtains zero energy gain after the laser pulse traverses it. For the second electron (with energy gain), it is accelerated and obtains kinetic energy, like the first one, at the ascending-part of the laser pulse. But at the descending-part of the pulse, the electron, while moving into the field-intensity decreasing region, is decelerated by a laser field of lower-intensity (relative to that at the ascending-part) owing to intensity-decreasing. Thus the electron returns less amount of the kinetic energy to the laser field in the deceleration. As a result, the electron retains an amount of kinetic energy and is emitted forward after the laser pulse traverses it.

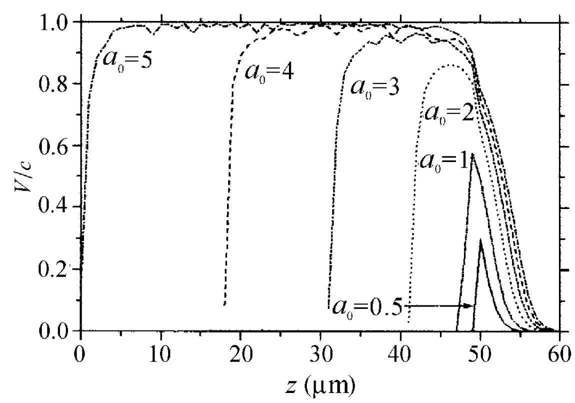

Fig. 1. Final velocities V/c of the electrons, after the laser pulse traverses them, as a function of their initial positions z for different a_0. The laser pulse propagates along the z-axis from left to right and its pulsewidth is 30 fs in FWHM. The laser's intensity begins to decrease at the position $z = 50$ μm with an attenuation coefficient $\alpha = 0.5/\mu$m.

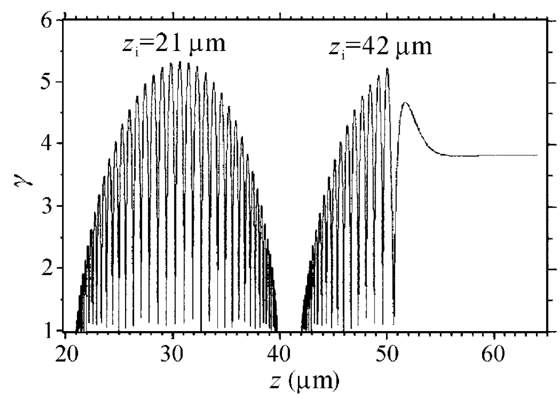

Fig. 2. The relativistic factors γ of two representative electrons as a function of their longitudinal positions z. The two electrons are initially at $z_i = 21$ μm and $z_i = 42$ μm, separately. For the laser pulse, $a_0 = 3$ and the other conditions are the same as described in Fig. 1.

Since electrons only in a limited region can obtain net energy gain in the acceleration, it provides a possibility that these electrons, as a pulsed beam, are of a bunch length on the order of femtoseconds. In Fig. 1, it is shown that for $a_0 = 3$, i.e. the laser peak intensity corresponding to 2×10^{19} W/cm^2, this limited region corresponds to a bunch length of 90 fs for the electron beam. Experimentally, if free electrons are initially confined in a narrower region, with a thin film target for example, the bunch length of the accelerated electron beam may be shorter. Recall that in the laser wakefield acceleration, the bunch length of the accelerated electron beams was usually limited by the lifetime of the plasma wave, on the order of picoseconds[14,15].

From Fig. 1, it is found that the maximum energy of the net-energy-gain electrons scales with the laser strength parameters as

$$\gamma_{\max} = 1 + \eta \cdot {a_0}^2, \qquad (6)$$

in which $\gamma_{\max}$ is the relativistic factor corresponding to the maximum energy, and $\eta = 0.43$ for the 30-fs laser pulse (see Fig. 3). Note this a_0-square scaling relation is comparable to that of the maximum energy of an electron in a plane electromagnetic wave in vacuum, which is given by $(1 + \frac{1}{2}{a_0}^2)mc^2$. But in the case of a plane electromagnetic wave, it is well known that an electron cannot gain net energy after the wave traverses it[12].

When a laser pulse's intensity decreases at a different rate, the maximum energy gain of the accelerated electrons is found to change evidently. Calculations for the same conditions as above otherwise $\alpha = 0.1/\mu$m show that the maximum energy gain of the accelerated electrons is smaller. In this case, $\eta = 0.28$. Therefore, the faster the laser's intensity decreases, the more efficiently the accelerated electrons gain net energy from the laser field.

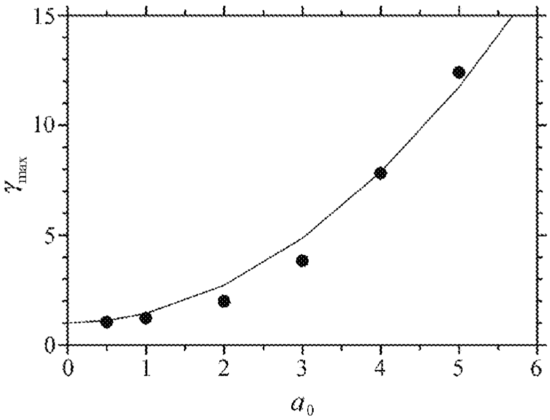

Fig. 3. The relativistic factor $\gamma_{\max}$ as a function of the laser strength parameter a_0. $\gamma_{\max}$ corresponds to the maximum of γ of the net-energy-gain electrons after the laser pulse traverses them. The solid curve is fitted by $\gamma_{\max} = 1 + 0.43a_0^2$.

The effect of the laser pulsewidth on the net energy gain is also considered by adapting a different pulsewidth in the calculations. With a longer pulsewidth, it is found that electrons initially in a wider region can gain net energy. The reason is that with the increasing of the laser pulsewidth, the longitudinal spatial extent corresponding to the ascending-part of the laser pulse increases, thus electrons in a wider region can move within the laser pulse envelope into the intensity-decreasing region. Therefore, for the purpose of generating an ultrafast electron beam, a shorter laser pulse is better.

Physically, there are several possible situations for the present mechanism to be responsible for the generation of energetic electron beams in high-intensity interaction experiments. A possible approach is to use a solid or a thin film target, with which a strong absorption of an intense laser pulse may happen in a distance on the order of the laser wavelength. Relative to the focal spot size ($\gtrsim 10$ μm) of the laser beam, the absorption may be regarded to happen in one-dimensional in the propagation direction. It has been reported that more than 40% of the laser energy can be absorbed in intense laser-solid interactions[3,16]. A gas-jet target may provide another approach. If a laser beam is focused at the edge of a gas-jet, in the laser-gas interaction region the laser pulse may experience intensity decreases due to diffraction, absorption and collective scattering, or beam breakup caused by relativistic filamentation. A strong correlation between the forward MeV-electron emissions and the relativistic filamentation has been reported[17].

In conclusion, we have shown a mechanism of net-energy gain of electrons accelerated by a propagating ultrafast, intense laser pulse whose intensity begins to decrease rapidly at some position along the direction of propagation. This net-energy-gain mechanism originates from the longitudinal ponderomotive laser acceleration and thus, the resulted energetic electrons are emitted in the directly forward direction. Such a mechanism may be used to generate a MeV electron beam with bunch length on the order of femtoseconds, with an ultrashort ($\lesssim 30$ fs), intense ($> 10^{19}$ W/cm^2) laser pulse. The generated electron beam may, as a seed, be trapped and further accelerated by plasma waves, or be applied either as a femtosecond injector for accelerators or as a beam for the generation of ultrafast radiation sources.

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