Laser Electron Accelerator

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An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2. On the other hand, the glass laser technology is capable of delivering a power density of 10^{18} W/cm^2, and, as we shall see, an electric field of 10^9 V/cm. We propose a mechanism for utilizing this high-power electromagnetic radiation from lasers to accelerate electrons to high energies in a short distance. The details of this mechanism are examined through the use of computer simulation. Meanwhile, there have been a few works for particle acceleration using lasers. Chan[4] considered electron acceleration of the order of 40 MeV with comoving relativistic electron beam and laser light. Palmer[5] discussed an electron accelerator with lasers going through a helical magnetic field. Willis[6] proposed a positive-ion accelerator with a relativistic electron beam modulated by laser light.

A wave packet of electromagnetic radiation (photons) injected in an underdense plasma excites an electrostatic wake behind the photons. The traveling electromagnetic wave packet in a plasma has a group velocity of $v_g^{\mathrm{EM}} = c(1-\omega_p^2/\omega^2)^{1/2} < c$, where ω_p is the plasma frequency and ω the photon frequency. The wake plasma wave (plasmon) is excited by the ponderomotive force created by the photons with the phase velocity of

$$v_p = \omega_p/k_p = v_g^{\mathrm{EM}} = c(1-\omega_p^2/\omega^2)^{1/2}, \tag{1}$$

where k_p is the wave number of the plasma wave.[7] Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p. \tag{2}$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate treatment. Consider the light wave propagating in the x direction with the electric field in the y direction. The light wave sets the electrons into transverse oscillations. If the intensity is not so large that the transverse motion does not become relativistic, then the mean oscillatory energy is $\langle \Delta W_T\rangle \cong m\langle v_y^2\rangle/2 = e^2\langle E_y^2\rangle/2m\omega^2$ where the angular brackets denote the time average. In picking up the transverse energy from the light wave, the electrons must also pick up the light wave's momentum $\langle \Delta p_x\rangle = \langle \Delta W_T\rangle/c$. During the time the light pulse passes an electron, it is displaced in x a distance $\Delta x = \langle \Delta v_x \tau\rangle$, where τ is the length of the light pulse. Once the light pulse has passed, the space charge produced by this displacement pulls the electron back and a plasma oscillation is set up. The wake plasmon, which propagates with phase velocity close to c [Eq. (1)], can trap electrons. The trapped electrons which execute trapping oscillations can gain a large amount of energy when they accelerate forward, since they largely gain in mass and only get out of phase with this wave after a long time.

Let us consider the electron energy gain through this mechanism. We go to the rest frame of the photon-induced plasmon. Since the plasma wave has the phase velocity v_p [Eq. (1)], we have $\beta = v_p/c$ and $\gamma = \omega/\omega_p$. Note that this frame is also the rest frame for the photons in the plasma; in this frame the photons have no momentum. The Lorentz transformations of the momentum four-vectors for the photons and the plasmons