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 $\sim 10^7$ 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

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

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:

$$L_t = \lambda_w/2 = \pi c/\omega_p. \qquad (2)$$

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

are

$$\begin{pmatrix} \gamma & i\beta\gamma \\ -i\beta\gamma & \gamma \end{pmatrix} \begin{pmatrix} k_x \\ i\omega/c \end{pmatrix} = \begin{pmatrix} 0 \\ i\omega_p/c \end{pmatrix}, \qquad (3)$$

$$\begin{pmatrix} \gamma & i\beta\gamma \\ -i\beta\gamma & \gamma \end{pmatrix} \begin{pmatrix} k_p \\ i\omega_p/c \end{pmatrix} = \begin{pmatrix} k_p/\gamma \\ 0 \end{pmatrix}, \qquad (4)$$

where the right-hand side refers to the wave frame quantities ($k_p^{\text{wave}} = k_p/\gamma$), k_x is the photon wave number in the laboratory frame and use was made of the well-known dispersion relation for the photon in a plasma $\omega = (\omega_p^2 + k_x^2 c^2)^{1/2}$. Equation (3) is reminiscent[8] of the relation between the meson and the massless (vacuum) photon: Eq. (3) indicates that the photon in the plasma (dressed photon) has the rest mass ω_p/c, because the electromagnetic interaction shielded by the plasma can reach only the collisionless skin depth c/ω_p just as the nuclear force reaches the inverse of the meson rest mass. At the same time, the Lorentz transformation gives the longitudinal electric field associated with the plasmon as invariant ($E_L^{\text{wave}} = E_L$).

The critical amplitude of the plasmon is determined by the wave-breaking limit. The oscillation length by the plasmon in one plasma period should not exceed the wavelength: $k_p x_L \simeq 1$, where $x_L \simeq eE_L/m\omega_p^2$.[7] From Gauss's law the critical longitudinal field attainable is

$$eE_L^{\text{cr}} \cong mc\omega_p. \qquad (5)$$

If follows from the E_L invariance and Eq. (4) that the wave potential in the wave frame becomes

$$e\varphi^{\text{wave}} = \gamma e\varphi \approx \gamma mc^2. \qquad (6)$$

An electron achieves maximum energy when it reverses its acceleration in the wave frame. Transforming the energy [Eq. (6)] and velocity in the wave frame to the laboratory frame, we obtain the maximum electron energy W^{max} through this process as

$$\begin{pmatrix} \gamma & -i\beta\gamma \\ i\beta\gamma & \gamma \end{pmatrix} \begin{pmatrix} \gamma\beta mc \\ i\gamma mc \end{pmatrix} = \begin{pmatrix} 2\gamma^2\beta mc \\ imc\gamma^2(1+\beta^2) \end{pmatrix}, \qquad (7)$$

of $W^{\text{max}} \equiv \gamma^{\text{max}} mc^2 \simeq 2\gamma^2 mc^2$. Therefore, we have

$$\gamma^{\text{max}} = 2\omega^2/\omega_p^2. \qquad (8)$$

The time t_a and length l_a for electrons to reach energies of Eq. (8) may be given by the relation $t_a \cong W^{\text{max}}/ceE_L^{\text{cr}}$ and $l_a \cong ct_a$ or

$$l_a \cong 2\omega^2 c/\omega_p^3. \qquad (9)$$

For the glass laser of 1-μm wavelength shone on a plasma of density 10^{18} (10^{17}) cm^{-3}, it would re-

quire under the present mechanism a power of 10^{18} (10^{18}) W/cm^2 to accelerate electrons to energies W^{max} of 10^9 (10^{10}) eV over the distance of 1 (30) cm with the longitudinal electric field E_L^{cr} of 10^9 (3×10^8) V/cm.

To demonstrate the present mechanism for electron acceleration, we have performed computer simulations employing the $1\frac{2}{2}$-D (one spatial and three velocity and field dimensions) relativistic electromagnetic code.[9] A finite-length train of electromagnetic radiation with wave number k_x is imposed on an initially uniform thermal electron plasma. The direction of the photon propagation, as well as of the allowed spatial variation, is taken as the x direction. The system has typically the length $L_x = 512\Delta$, the speed of light $c = 5v_e$, the photon wave number $k_x = 2\pi/15\Delta$, the number of electrons 5120, and the particle size 1Δ with a Gaussian shape, and the ions are fixed and uniform, where Δ and v_e are the unit spatial grid distance and the electron thermal speed, respectively. In order to effectively change the ratio ω/ω_p, we have changed c, keeping the following relations fixed: $eE_0/m\omega = eB_0/m\omega = c$, $L_t = \pi c/\omega_p$ [Eq. (2)], $p_0 = eE_0/\omega$, and $\omega = (\omega_p^2 + k_x^2 c^2)^{1/2}$, where E_0 and B_0 are the pump-wave electric and magnetic field amplitudes and p_0 is the corresponding amplitude for the momentum modulation. We have run cases with $c = (5, 7.25, 10,$ and $14.7)\omega_p\Delta$. The initial pump wave has the form of $E_y = E_0 \sin k_x(x - x_0)$, $B_z = B_0 \sin k_x(x - x_0)$, and $p_y = p^{\text{random}} + p_0 \cos k_x(x - x_0)$ for the interval of $x = [50\Delta, 81.4\Delta]$ with $x_0 = 50\Delta$. With this assignment, the wave packet has a spectrum in k with a peak around $k = k_x$ and $\omega = (\omega_p^2 + k_x^2 c^2)^{1/2}$, and propagates in the forward x direction approximately retaining the original polarization. In this series of simulations, a run with larger c means larger ω, longer photon train L_t, and stronger E_0, since ω_p is taken to be constant.

Figure 1 shows an early stage of the system development. The phase-space plot [p_y vs x in Fig. 1(b)] indicates a strong modulation in the p_y distribution within the photon wave-packet location. A kink structure extends behind the packet ending at the packet starting point ($x \sim 50\Delta$) with a net motion of the particles in the positive p_y direction. Figure 1(a) shows p_x vs x; this should be compared to Fig. 1(b). The intense longitudinal momentum oscillations are clearly shown, beginning at the photon wave packet and extending back to its initial position. This is the wake plasma wave excited by the photons. Note that
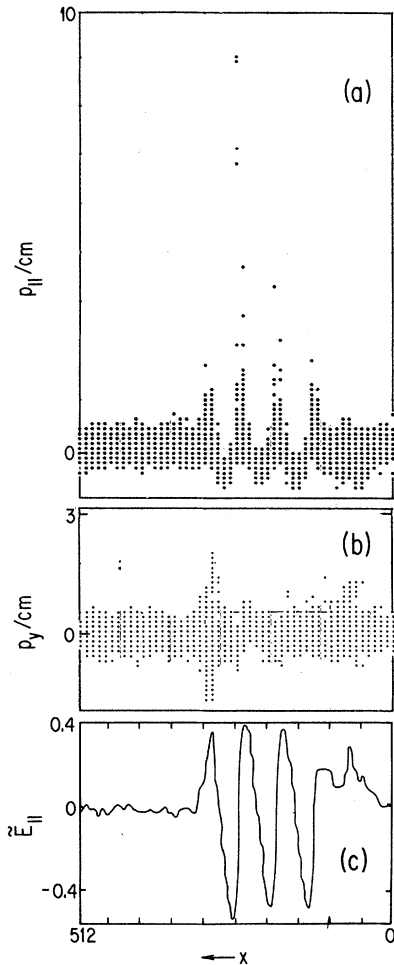
FIG. 1. Wake-plasmon excitation and trapping of electrons. The head of the photon packet has proceeded forward to $x = 310$ at $t = 24\omega_p^{-1}$. $\omega/\omega_p = 4.3$. (a) The longitudinal momentum $(p_x = p_\parallel)$ vs position $(p_x\text{-}x$ phase space) of electrons. (b) $p_y\text{-}x$ phase space. (c) The longitudinal field $E_L = E_\parallel$ vs position.

FIG. 2. (a) Spectral intensity of electromagnetic waves in wave number k. The arrow with 0 indicates the rough position of the original peak; n indicates k' $= k \pm nk_p$ with $k_p = \omega_p/c$. (b) Maximum electron energy vs $(\omega/\omega_p)^2$. The dots are from simulation results and the solid line from Eq. (8).

already a set of electrons is accelerated to large positive p_x momenta by the wake plasmon, exemplified by the long stretching armlike phase-space pattern [Fig. 1(a)]. These arms keep stretching to large momenta.

The wake plasmon structure is also apparent in the plot of the longitudinal electric fields [Fig. 1(c)]. The longitudinal field strength reaches values around $E_L \sim 0.6 mc\omega_p/e$ [cf. Eq. (5)] or 0.6 of the theoretical maximum value for a cold plasma. As time progresses, the photons continue to emit the plasmon wake leaving a longer and longer plasma wave train. Figure 2(a) shows the wave-number spectrum of the electromagnetic pulse at successive times. The original smooth-
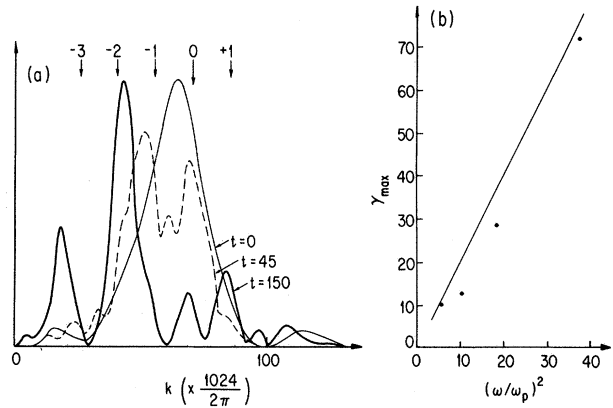
shaped spectrum evolves into a multipeak structure with a roughly equal, but slightly increasing, separation in wave number as k approaches k_p. This indicates that the photons with peak wave number k_x decay into the photons with $k' \cong k_x$ $- nk_p$ and $\omega' = \omega - n\omega_p$ (n an integer) through successive or multiple forward Raman scattering instabilities. As ω' decreases, the photon group velocity decreases. This process is simply the photon deceleration caused by the emission and drag of the wake plasmons. The possibility of multiple forward Raman scattering may relax the condition in Eq. (2), since the forward Raman instability itself creates wake plasmons. Also, this possibility of acceleration by the forward Raman scattering[10] may raise a serious problem of high-energy electrons in the laser fusion experiment. An arm of accelerated particles stretches from each plasma wavelength and constitutes approximately 1% of the total electron population in this simulation. The longitudinal electron momenta and the total longitudinal electric field energy typically increase linearly in time until saturation.

For various photon frequencies (ω/ω_p), we measure the maximum electron energy achieved. The simulation results are given by the dots in Fig. 2(b). These points should be compared with the theoretical prediction, Eq. (8) (solid line). We find that the (ω/ω_p) characteristics of the attainable electron energy by simulations, indeed, follow very closely Eq. (8). Because of the finite system size and the periodic boundary conditions,

the interference of the wake fields becomes significant beyond $(\omega/\omega_p)^2 \sim 40$. To extend the simulations to really high energy, one needs much longer system size for the simulation; however, since the scaling agrees with Eq. (8) we can use it with some confidence there.

The present mechanism of electron acceleration seems feasible within present-day technology. Although the pulse lengths of $(2n+1)\pi c/\omega_p$ are also allowed, techniques of making short pulses have to be perfected (e.g., pulse chopping by backscattering). Having two laser beams with $\Delta\omega = \omega_p$ as mentioned above is an alternative.

We may speculate that the present acceleration process may play a role in such an environment as a pulsar atmosphere, where the dipole radiation fields can be so large that $eE/m\omega \gg c$. In the early life of a pulsar when the blowoff plasma, still not far from the pulsar, faces these intense fields, the pulsar plasma can be a strong cosmic-ray source through this mechanism.

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[7]Conditions $eE/m\omega = c$ for electromagnetic and $eE_L/m\omega_p \cong c$ for electrostatic waves change the plasma frequencies only slightly, because particles acquire relativistic momenta only at the peak of the oscillations, except for the trapped electrons for longitudinal oscillations whose population is a fraction of the total. Highly relativistic cases ($eE/m\omega > c$) have magnetic acceleration as well.

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Neutral-Beam-Heating Results from the Princeton Large Torus

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Experimental results from high-power neutral-beam—injection experiments on the Princeton Large Torus tokamak are reported. At the highest beam powers (2.4 MW) and lowest plasma densities $[n_e(0) = 5\times10^{13}$ cm$^{-3}]$, ion temperatures of 6.5 keV are achieved. The ion collisionality ν_i^* drops below 0.1 over much of the radial profile. Electron heating of $\Delta T_e/T_e \approx 50\%$ has also been observed, consistent with the gross energy-confinement time of the Ohmically heated plasma, but indicative of enhanced electron-energy confinement in the core of the plasma.

The purpose of the Princeton Large Torus (PLT) tokamak neutral-beam—injection experiments is to produce collisionless high-temperature tokamak plasmas in which to study ion and electron thermal transport. In this paper we present data from recent neutral-beam—heating experiments on the PLT tokamak, extending the results of previous injection-heating experiments,[1-6] to the better confinement conditions associated with large tokamaks, and also extending our pre-