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AN ELECTRON ACCELERATOR USING A LASER

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Abstract

An intense electromagnetic pulse (photon pulse) of proper length can create a wake of plasma oscillations (plasmon wake) through the action of the nonlinear ponderomotive force. The phase velocity of the wake is equal to the group velocity of the light pulse which can be only slightly less than the velocity of light in a vacuum. The electric fields in the wakes can be quite intense (up to order $eE = mc/\omega_p$). Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shined on plasmas of densities 10^{18}cm^{-3} can yield GeV energy electrons per cm. The mechanism for this acceleration is examined and its details are demonstrated through computer simulation. Applications to accelerators and pulsars are examined.

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Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Veksler[1] has suggested a scheme of accelerating particles through collective mechanism using an electron stream. Earlier Fermi[2] and McMillan[3] considered cosmic ray particle acceleration by moving magnetic fields[2] or electromagnetic waves.[3] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[4] yield electric field of ~10^7V/cm and power density 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 10^9V/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. On the other hand, a few works have been reported for the particle acceleration using lasers. Chan[5] considered electron acceleration of the order of 40 MeV with co-moving relativistic electron beam and laser light. Palmer[6] discussed an electron accelerator with lasers going through a helical magnetic field. Willis[7] proposed a positive ion accelerator with a relativistic electron beam modulated by laser light.

A wavepacket of electromagnetic radiation (photons) injected in an underdense plasma excites an electrostatic wake behind the photons. The traveling electromagnetic wavepacket in a plasma has a group velocity of $v_g^{EM} = c(1 - \omega_p^2/\omega^2)^{1/2} < c$, 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

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

where k_p is the wavenumber of the plasma wave. Such a wake is most effectively generated if the length of the electromagnetic wavepacket is half the wavelength of the plasma waves in the wake:

$$L_t = \frac{\lambda w}{2} = \pi c/\omega_p . \qquad (2)$$

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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 $\langle \Delta W_T \rangle \cong m \langle v_y^2 \rangle /2 = e^2 \langle E_y^2 \rangle / 2m\omega^2$; on the other hand for strongly relativistic transverse motion $\langle \Delta W_T \rangle \cong e \langle |E_y| \rangle c$ where the $\langle \quad \rangle$ denote the time average. In picking up the transverse energy from the light wave the electrons must also pick up the light waves 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 plasma wave, 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 longitudinal wave (plasmon). Since the wave has the phase velocity Eq. (1), $\beta = v_p/c$ and $\gamma = \omega/\omega_p$. Note that this frame is also the rest frame for the photons in the plasma; in this frame k for the photons is zero (they have no momentum). The Lorentz transformations of the momentum 4-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 rest frame quantities ($k_p^{rest} = k_p/\gamma$), k_x is the photon wavenumber in the laboratory frame and the well-known dispersion relation for the photon in a plasma $\omega = (\omega_p^2 + k_x^2 c^2)^{1/2}$ was used. Equation (3) is reminiscent[8] of the relation between the meson and the massless (vacuum) photon, since Eq. (3) indicates that the photon in the plasma (dressed photon) has the rest mass ω_p/c while the vacuum photon has no rest mass as the plasma density vanishes ($\omega_p \to 0$). At the same time, the Lorentz transformation gives the longitudinal electric field associated with the plasmon as invariant ($E_L^{rest} = E_L$).

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 $x_L \simeq eE_L/m\omega_p^2$. Therefore, the critical longitudinal field attainable is

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

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

$$e\phi^{rest} = \gamma e\phi \simeq \gamma mc^2 \ . \qquad (6)$$

In the rest frame an electron achieves maximum energy when it reverses its acceleration. Transforming the velocity v_p in the wave frame to the rest frame, we obtain the maximum electron energy through this process as

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

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

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

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

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

For the glass laser of 1 μ wavelength shined on a plasma of density 10^{18} (10^{17}) cm^{-3}, it would require 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 $10^9 (3 \times 10^8)$ V/cm .

It is more difficult to trap and accelerate ions by the mechanism presented here. However, if the ions are preaccelerated and/or the plasma density decreases in space in the photon propagation direction so that the group velocity matches the ion velocity, the laser light may also be able to trap and accelerate ions to high energies. Consider, for example, a case where the ion energy attained by the ponderomotive potential is non-relativistic: $e\phi^{rest} \simeq \gamma mc^2 \simeq Mv_i^2/2$, where M and v_i are the ion mass and velocity in the rest frame. The Lorentz transformation as per Eq. (7) yields in this case the maximum attainable ion energy.

$$W_i^{max} \simeq (\omega/\omega_p)\ Mc^2[1+(2\omega/\omega_p)^{\frac{1}{2}}(m/M)^{\frac{1}{2}}] \ . \qquad (10)$$

To demonstrate the present mechanism for electron acceleration, we have performed computer simulations employing the 1-2/2 D (one spatial and three velocity and field dimensions) relativistic electromagnetic code[9] with the periodic boundary conditions. A finite-length train of electromagnetic radiation with wavenumber 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 the x direction. The number of runs of our computer simulation have clearly demonstrated the present mechanism up to $(\omega/\omega_p)^2 \simeq 40$: The simulation results for the maximum electron energy closely follow Eq. (8). Beyond $(\omega/\omega_p)^2 \simeq 40$, because of the code's periodic boundary conditions and finite length, the photon/plasmon re-entry from the other end interferes with the simulation. To extend the simulations to really high energy, one needs much longer system size for the simulation than the one we have done; however, since the simulation scaling agrees with Eq. (8), we can use it with some confidence there.

As the photon wavepacket progresses in the plasma, the photons continue to emit the plasmon wave leaving a longer and longer plasma wave train. The spectral intensity S(k) of the photons in wavenumber in the simulation shows that the original round Gaussian-like shaped spectrum evolves into a multi-peak structure with a roughly equal but slightly increasing separation in wavenumber as k decreases towards k_p. This indicates that the photons with peak wavenumber k_x and frequency ω decay into the Stokes photons with $k' \simeq k_x - nk_p$ and $\omega' = \omega - n\omega_p$ (n: interger) 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 the multiple forward Raman scattering may relax the condition, Eq. (2), since the forward Raman instability itself creates wake plasmons. However, if the train length becomes too long, the stronger and unfavorable Raman backscattering may come into play. This multiple forward Raman scattering of the photon wavepacket may be looked upon as a "Cherenkov" process where the photon in the plasma emits plasmons (and electrons). Note here that the photon plays the role of the electron in the ordinary Cherenkov radiation and the plasmon the role of the radiation. One might, therefore, expect a "Cherenkov shock cone" by the emission of plasmons.

The present mechanism of electron acceleration seems feasible within the present-day laser technology to have an interesting and attractive accelerator. We may speculate that the present acceleration process may play a role in such an environment as a pulsar atmosphere[10], where the dipole radiation fields can be so large that $eE/m\omega c \sim 10^{11-13}$ for the Crab pulsar, for example. In the early life of a pulsar when the blow-off plasma still not far away from the pulsar sees these intense fields, the pulsar plasma can be a strong cosmic ray source through this mechanism. As the pulsar gets older and the blow-off plasma expands, this process may become more difficult to take place.

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