Electron acceleration in a strong laser field and a static transverse magnetic field

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A method is proposed for using focused laser light to accelerate electrons in a static transverse magnetic field. A relationship which must hold between the magnetic field strength and the parameters of the laser beam is found.

Among the various schemes presently being discussed for laser acceleration of electrons,[1] those which do not require the use of a plasma or any other medium are of particular interest. Such schemes have the advantage that high laser light intensities can be used. One of these schemes is the noncollinear inverted Compton laser, which we have discussed previously.[2] A disadvantage of the method described in Ref. 2 is the comparatively low acceleration rate; another is the need for two lasers, with approximately the same wavelength and with high-power densities in large focal volumes.

In the present letter we analyze laser acceleration of electrons in a static transverse magnetic field.

Let us examine the motion of an electron in a uniform static magnetic field H and in the field of an electromagnetic wave, in the geometry shown in Fig. 1. Here d and L are the transverse and longitudinal dimensions of the caustic, and $R = c/\Omega$ is the Larmor radius, where $\Omega = eHc/\epsilon_0$ is the cyclotron frequency, $\epsilon_0 = \gamma mc^2$ is the initial energy of the electron, and γ is the relativistic factor. We assume that the field of the laser light is polarized along the x axis and that the electric field of the wave, $\mathbf{E} \| x$, is of the form

$$E = E_0(x, z)\cos(\omega(t - z/c) + \varphi_0), \qquad (1)$$

where E_0 is an amplitude which varies slowly over distances on the order of the wavelength, and φ_0 is the constant phase. The rate of change of the energy of an electron in the fields E and H is determined by the equation

$$d\epsilon/dt = -eV_x E, \qquad (2)$$

where v_x is the x projection of the electron velocity.

In the absence of a radiation field ($E = 0$) we would have $\epsilon = \epsilon_0 = \text{const}$, and the solution of the equations of motion of the electron would be

$$z^{(0)} = z_0 + \frac{v_0}{\Omega}\sin\Omega t \qquad x^{(0)} = x_0 + \frac{v_0}{\Omega}(1 - \cos\Omega t), \qquad (3)$$

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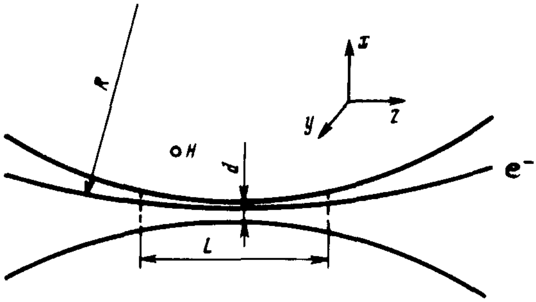

FIG. 1. Geometry of this method for accelerating electrons.

where x_0 and z_0 are the coordinates of the electron at time $t=0$. For convenience, we choose this time to satisfy $\dot{x}^{(0)}(t=0)=0$.

Assuming that the perturbations of the motion of the electron by the laser field are small, we find the change ($\Delta\epsilon$) in the energy of the electron in first order in E by substituting the zeroth-order solution (3) into the right side of Eq. (2). We assume that the Larmor radius R is large in comparison with the dimensions of the caustic: $R \gg L \gg d$. Under this condition we can make use of the small quantity Ωt in equations of motion (3), and we can expand $\sin \Omega t$ and $\cos \Omega t$ in Taylor series, retaining terms of order up to $\sim (\Omega t)^3$ inclusively. As a result, we find an integral of the following type for the change in the energy of the electron:

$$\Delta\epsilon^{(1)} = - ec\Omega\,(2/\Omega^2\omega)^{2/3} \int_{-\infty}^{\infty} \tau d\tau\, E_0\Big(\frac{\Omega}{2}(2/\omega\Omega^2)^{2/3} c\tau^2 + x_0\,, \quad z_0 + (2/\Omega^2\omega)^{1/3} c\tau\Big) \cos\Big(\zeta\tau + \frac{\tau^3}{3} + \varphi_0\Big)\,, \tag{4}$$

where $\tau = (\omega\Omega^2/2)^{1/3} t$ is the dimensionless time, and $\zeta = (1/\gamma^2)(\omega/2\Omega)^{2/3}$.

A further simplification of this expression is possible if the cyclotron frequency Ω satisfies the condition

$$\frac{c}{L} \gg \Omega \gg \frac{1}{\omega^{1/2}} \left(\frac{c}{L}\right)^{3/2} \tag{5}$$

Here we can assume $E_0 = \text{const}$; from Eq. (4) we find

$$\frac{\Delta\epsilon^{(1)}}{\epsilon_0} = - \frac{2}{\sqrt{\pi}} \frac{eE_0\lambda}{mc^2} \sin\varphi_0 \sqrt{\zeta} \frac{d}{d\zeta} \Phi(\zeta)\,, \tag{6}$$

where

$$\Phi(\zeta) = \frac{1}{\sqrt{\pi}} \int_0^{\infty} \cos\Big(\zeta x + \frac{x^3}{3}\Big) dx \tag{7}$$

is the Airy function,[3] and λ is the wavelength of the light.

Plotted as a function of ζ, the function $\Delta\epsilon/\epsilon$, given by (6), goes through a maximum at $\zeta \sim 1$. The condition $\zeta \sim 1$ determines the optimum value of γ:

$$\gamma = (\omega mc/2eH)^{1/2}. \quad (8)$$

The quantity $\Delta\epsilon^{(1)}$ in (6) depends on the phase of the field at the time $t = 0$, when the electron velocity is parallel to the z axis. Only some of the electrons are accelerated by the field (specifically, those for which the condition $\sin\varphi_0 < 0$ holds).

Let us find some estimates. We assume $L = 2\times 10^{-1}$ cm and $\lambda = 10^{-3}$ cm (a CO_2 laser beam with $\omega = 2\times 10^{14}\ s^{-1}$). Constraints (5) take the following form in this case:

$$1.5\times 10^{11} > \Omega > 4\times 10^{9} \qquad 60\ \text{kG} > H > 2\ \text{kG}. \quad (9)$$

With $H = 20$ kG ($\Omega = 2\times 10^{10}\ s^{-1}$), condition (8) is satisfied at $\gamma \approx 17$.

At a laser light intensity $I = 10^{14}$ W/cm^2 we have $eE_0\lambda/mc^2 = 0.5$ and $(\Delta\epsilon/\epsilon)_{max} \approx 1$. This estimate indicates a high acceleration efficiency and also that the value $I \sim 10^{14}$ W/cm^2 is a limiting intensity, specifically, the highest intensity at which we can use perturbation theory if the interaction of the laser light with the field is taken into account. At high intensities we need a complete solution of the equations of motion of an electron in the fields E and H. Such calculations could hardly be carried out analytically; corresponding numerical calculations have been carried out.

Figure 2 shows the increment in the electron energy, $\Delta\epsilon$, versus the initial phase φ_0. We see that the interval of phases in which the electrons are accelerated becomes wider with increasing intensity of the electromagnetic field. At a field of 3.3×10^{15} W/cm^2, for example, more than 78% of the initial electrons become drawn into the acceleration, and $\approx 50\%$ of the injected electrons are accelerated to an energy above 5 MeV.

Figure 3 shows the increment in the electron energy as a function of the power density of the laser light. Perturbation theory predicts that this increment will be proportional to the value of E, while the results of the numerical calculations indicate

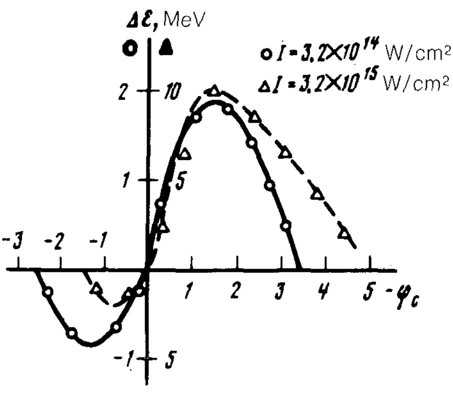

FIG. 2. The increment in the electron energy, $\Delta\epsilon$, versus the initial phase φ_0. $\epsilon_0 = 5.5$ MeV, $H = 20$ kG, $d = 200\ \mu$m, $L \approx 3$ mm, $\lambda = 10.6\ \mu$m.

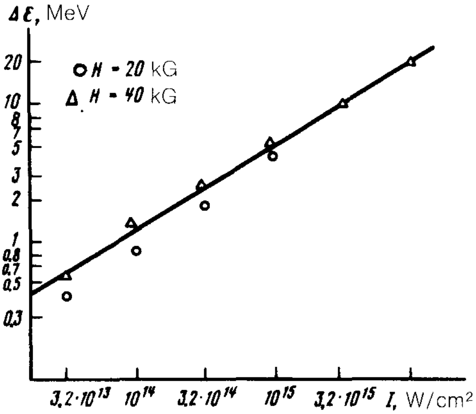

FIG. 3. Increment in the electron energy, $\Delta\epsilon$, versus the power density of the laser light. I. $\epsilon_0 = 5.5$ MeV, $d = 200$ μm, $L \approx 3$ mm, $\lambda = 10.6$ μm, $\varphi_0 = -1.57$.

$\Delta\epsilon \sim E^{1.2}$. The discrepancy seems to be a consequence of deviations from the perturbation theory.

In summary, the efficiency of the acceleration of electrons by this mechanism is extremely high. No "saturation" of this method is observed at intensities up to $\sim 10^{16}$ W/cm^2. The phase selectivity, which is inherent in this method in weak electromagnetic fields, is suppressed to a large extent at high intensities. An extremely large fraction of the electrons is drawn into the acceleration, and accelerators of this sort could be cascaded without an appreciable loss of luminosity of the original electron beam. The simplicity of design and the possibility of producing a static magnetic field of arbitrary configuration for focusing an electron beam by means of a fringing magnetic field would also facilitate cascading. They would make possible a cyclic acceleration of electrons in a single focal volume in a system using a train of short pulses.

[1]A. M. Sessler, "Report of the working group on other acceleration schemes," in: Proceedings, Laser Acceleration, Part 2, Workshop, Malibu, Calif., Jan. 7–18, 1985, New York; J. D. Lawson, "Laser accelerators: Where do we stand?" in: Proceedings, CAS-ECFA-INFN Workshop, Frascati, 1984, pp. 3–12.
[2]V. V. Apollonov, Yu. L. Kalachev, A. M. Prokhorov, and M. V. Fedorov, Appl Phys. Lett. **49**, 1668 (1986).
[3]L. D. Landau and E. M. Lifshitz, Quantum Mechanics: Non-Relativistic Theory, Pergamon, New York, 1977, Sec. C.

Translated by Dave Parsons