Acceleration of charged particles by ultrashort light pulses which create a space-charge front at the axis of a channel in a medium

G. A. Askar'yan
Institute of General Physics, Academy of Sciences of the USSR

(Submitted 26 July 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 6, 943–945 (25 September 1990)

The entry of an intense ultrashort light pulse into a channel in a medium causes charged plasma to form by relativistic photoelectrons. At the leading edge of this plasma, longitudinal field $\gtrsim 1$ GV/cm can arise. These fields could be utilized to accelerate particles to energies $\gtrsim 1$ GeV. The energies and lengths which the light pulses would have to have are estimated.

Intense ultrashort light pulses ($\tau \approx 10^{-14}$–10^{-11} s) have recently been the subject of some discussion, and major progress has been achieved[1,2] in their production. It is already possible to achieve relativistic oscillation velocities of free electrons, $v_e \approx eE/m\omega \approx c$, e.g., at $E_c > m\omega c/e = mc^2/e\lambda = e/r_0\bar{\lambda} \approx 10^8$–$10^7$ abs at reduced wavelengths $\bar{\lambda} = c/\omega \approx 10^{-5}$–$10^{-4}$ cm). The corresponding flux density are $I_c \approx E_c^2/4\pi \approx 3\times 10^{16}$–$3\times 10^{18}$ W/cm^2; respectively. (Here e, m, and r_0 are the charge, mass, and classical radius of the electron; and ω and E are the frequency and amplitude of the light wave.)

The appearance of such intense short pulses has made it possible to effectively realize, at a high output-power level, such new nonlinear effects of Čerenkov radiation from light bunches,[3,4] pronounced frequency conversion, the acceleration of particles by moving field gradients or plasma waves,[5] new types of photoelectron ionization,[6] and the production of ultrashort bursts of photons and photonuclear reactions.[7]

0021-3640/90/180323-04$01.00

In the present letter we discuss effects associated with the formation of a relativistic charged plasma when a light pulse of this sort is incident on a channel in a medium. We also discuss possibilities for the acceleration of charged particles. For simplicity we assume that the fields are such that the oscillation velocities of the electrons appearing in the photoelectric effect at the channel surface are close to (but not very close to) the velocity of light.

The role played by the channel walls reduces primarily to one of furnishing a large number of photoelectrons, which are torn out of the medium at relativistic velocities. The high fields would apparently make the efficiency of this photoelectric effect extremely high, and the number of electrons formed would be determined by the ratio of the absorbed energy to the oscillation energy, $N_{e1} \sim \mathscr{E}_1/mc^2$. Over a time $\tau_i \lesssim a/v_i$, however, before the ions are able to catch up with the electrons, the influx of electrons into the channel would be limited by the Coulomb potential. If we assume a channel radius $a \approx 30\ \mu$m, then the electron time will be $\tau_e \approx a/c \approx 10^{-13}$ s, and the ion time $\tau_i \approx a/v_i \approx 10^{-11}$ s, since we have $v_i \approx \sqrt{\epsilon_e/M_i} \approx 3\times 10^8$ cm/s. Over a time $t<\tau_i$ the electron density in the channel will be determined from the condition that the Coulomb potential be comparable to a relativistic energy:

$$V \approx 2\gamma \ln(a/r_1) \approx 2mc^2/e\ ,$$

where γ is the charge per unit length of the electron cloud in the channel, and r_1 is the effective radius of this cloud. If the scatter in the electron momenta is large, we can assume $\ln(a/r) \approx 1$ for estimates; we then find a radial field $E_r = V/a \approx 2mc^2/ae \approx 10^6$ abs ≈ 0.3 GV/cm. The longitudinal field $E_z \approx \gamma \int_{r_1} (dz/z^2)$ at the leading edges of the electron plasma at the channel axis will be of the same magnitude.

In addition to the oscillations, the electrons acquire a directed velocity which depends on the phase at which they enter the field (on the time at which the electron is torn out of the medium and enters the oscillation regime). For strong fields and low binding energies, the entrance phase will be such that the directed component of the velocity will be comparable to the oscillatory component, and the electrons will move toward the channel axis.

In a field $E=E_c \sin \omega t$, for example, we find (with homogeneous initial conditions for the electron at the entrance time t_1) a velocity $\dot{x} \approx v_c(\cos \omega t_1 - \cos \omega t) \approx v_c(\pm 1 - \cos \omega t)$, since at strong fields and with low electron binding energies the entrance phase with directed velocities takes on the values $\omega t_1 \to 0$, π, 2π, etc.

A time-varying acquisition of directed velocity is possible not only through the liberation of an electron from its bond at the appropriate starting time but also for free electrons, with sharp variations in the amplitude of the light pulse, e.g., at the front or end of the phase, during the abrupt entrance of an electron into a skin layer, etc.

If the starting conditions for the tearing of the electrons out of the medium and for the electron oscillations are approximately the same, and when the magnetic field of the light wave is taken into account, accumulations of charge may arise near the axis, at small radii, with a rod or tubular shape with a radius $r_1 \lesssim 0.1a$. In this case, far stronger fields, $E_z \sim E_r \sim 2mc^2 r_1 e \ln(a/r_1) \gtrsim$ GV/cm, can arise.

In these ultrastrong fields, the energy of the light, $\mathscr{E}_1 \approx \gamma mc^2/e \approx$ J/cm, will be expanded primarily on the formation of relativistic electrons. The rest of the energy will be reflected and will extend the caustic in the channel. By selecting the appropriate divergence of the light in the channel (by choosing the appropriate relationship between the radius and length of the focal spot and the radius and length of the channel), one can arrange acceleration lengths up to several centimeters and accelerate electrons to energies of several GeV.

There is the possibility of controlling the dynamics of the acceleration by varying the channel radius $a(z)$. This variation will cause a greater change in the formation of the acceleration front, which will occur after a delay of $a(z)/c\cos\theta$ with respect to the pulse front.

The strong accelerating fields and the short acceleration path lengths simplify the achievement of the acceleration regime and the maintenance of this regime, because the differences between the path lengths of the particles and the length of the accelerating front will be small.

Specifically, if there is reflection from the channel walls, the group velocity of the pulse will be

$$v_{\rm gr} = c\sqrt{1-\lambda^2/\lambda_{\rm cr}^2} \approx \zeta c = (1 - {}^1/_2 \times 10^{-5})\, s,$$

i.e., extremely close to the velocity of light in vacuum under our conditions, with a critical wavelength $\lambda_{\rm cr} \approx 3.4a \approx 10^2$ μm and $\lambda \approx 0.3$ μm.

The distance traversed by the particles to be accelerated, $z(t)$, can be found by integrating the momentum change $(d/dt)(\beta/\sqrt{1-\beta^2}) = (F/mc)$ twice. For a zero starting velocity, we find

$$z = (mc^2/F)\,\{\sqrt{1+(Ft/mc)^2} - 1\}.$$

Assuming an acceleration time $T = L/v_{\rm gr}$, we find the difference between the path lengths transversed by the electrons and by the pulse to be

$$\Delta = z(T) - L = (mc^2/F)\{\sqrt{1+(FL/mc^2\zeta)^2} - 1\} - L \approx L({}^1/_\zeta - 1) - (mc^2/F) \lesssim r_1$$

under our conditions, with $FL/mc^2 \approx 10^3 \gg 1$.

The number of accelerated particles can be estimated from the condition that the charge being accelerated is comparable to the charge of the front that performs the acceleration: $q_{\rm fr} \sim \gamma r_1 \sim 1$ abs. The corresponding number of particles is $N_{\rm acc} \sim q_{\rm fr}/e \approx 10^9$. An annular structure of the leading edge might keep the acceleration stable in the radial direction. It would apparently be possible to achieve acceleration at the many fronts which would form if the pulse had many pulsations or in each period.

Such an acceleration might be used to accelerate muons and pions, as well as electrons. It would be possible to achieved "pulling" versions as well as "pushing" versions, e.g., by using the trailing edge of a pulse at the front at which a charge accumulation disappears. In other words, it would be possible to accelerate particles differing in sign.

[1] K. Boyer and C. H. Rhodes, Phys. Rev. Lett. **54**, 1490 (1985).
[2] C. H. Rhodes, Science **229**, 1345 (1985).
[3] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. **42**, 1360 (1962) [Sov. Phys. JETP **15**, 943 (1962)]; Zh. Eksp. Teor. Fiz. **45**, 643 (1963) [Sov. Phys. JETP **18**, 441 (1963)]; Phys. Rev. Lett. **57**, 2470 (1986).
[4] D. H. Auston, Appl. Phys. Lett. **43**, 713 (1983); D. H. Auston, I. A. Valdmanis, and D. A. Kleinman, Phys. Rev. Lett. **53**, 1555 (1984).
[5] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[6] I. L. Beĭgman and B. N. Chichkov, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 314 (1987) [JETP Lett. **46**, 395 (1987)].
[7] G. A. Askar'yan, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 179 (1988) [JETP Lett. **48**, 193 (1988)].

Translated by D. Parsons