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CHARGED PARTICLE ACCELERATION IN NONUNIFORM PLASMAS

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Abstract

We consider the interaction of high-intensity laser pulses with nonuniform underdense plasmas and address the problem of the excitation of strong wake plasma waves with regular electric fields that can provide high acceleration rate of charged particles.

I. INTRODUCTION

The high-gradient electron acceleration schemes that have been demonstrated using LWFA [1,2] appear promising for the development of plasma-based laser accelerators into practical devices. However, a question still exists: how to avoid the wake field deterioration and the loss of the phase synchronism between the plasma wave and the electrons that prevent them from being accelerated up to the theoretical limit that corresponds to $\gamma_{\max} \approx \left(\omega / \omega_p\right)^2$ [3] and can be even as high as $a\left(\omega / \omega_p\right)^3$ [4,5]. Here γ is the Lorentz factor, ω is the laser frequency, ω_p is the Langmuir frequency, and $a \equiv eE_\perp / m\omega c$ is the dimensionless amplitude of the laser radiation.

In order to obtain the highest possible values of the wake electric field we must use as intense laser pulses as possible i.e., pulses with dimensionless amplitudes $a >> 1$. When $a << 1$, we have $a \approx v_{osc} / c$, where v_{osc} / c is the ratio of the electron oscillation velocity in the pulse to the speed of light.

Pulses that have a dimensionless amplitude larger than one tend to be subject to a host of instabilities, such as relativistic self-focusing, self modulation and stimulated Raman scattering, that affect their propagation in the plasma. Such processes could be beneficial, in so far as they increase the pulse energy density, enhance the wake field generation, and provide the mechanism for transporting the laser radiation over several Rayleigh lengths without diffraction spreading. However, it is still far from certain that these processes can be exploited in a controlled form and can lead to regular, stationary wake fields.

It is known that, in order to create good quality wake fields, it would be preferable to use laser pulses with steep fronts of order λ_p [5,6]. The present paper aims at analyzing the influence of the laser pulse shape and of the plasma nonuniformity on the charged particle acceleration. This study is based on the results obtained with one dimensional PIC simulations. In these simulations circularly polarized laser pulses with amplitude $a \approx 1$ and different profiles interact with nonuniform plasmas. An electron beam of test particles with random momentum distribution in the interval $0 \div 5mc$ is used to determine the maximum acceleration rate and the energy of the accelerated particles.

II. PRODUCTION OF PULSES WITH SHARP FRONTS

The feature of the pulse that is specifically responsible for providing good conditions for particle acceleration is the sharp rise of the pulse front. Sharpening of relativistically intense pulses propagating in an underdense plasma via the backward stimulated Raman scattering process has been observed in [7] and [8].

Here we consider another method for producing laser pulses with sharp fronts which consists of transmitting the pulse through a thin foil. The results obtained with the UMKA2D3V code simulations for this case are illustrated in Fig. 1. Sharpening of relativistically intense pulses interacting with a thin slab of the overdense plasma has been observed in the 1D PIC computer simulations presented in Ref. [5].

In Fig. 1 the results of simulations for a pulse with initial amplitude $a=1$, pulse length 10λ, and width 5λ, with foil thickness equal λ, and plasma density corresponding to $\omega/\omega_p=1.1$ are presented. As a result of the interaction, a sharp, $\approx 3\lambda$ long, leading edge is produced. In addition we can see a sharp, $\approx 3\lambda$ long, rear edge of the reflected part of the laser pulse.

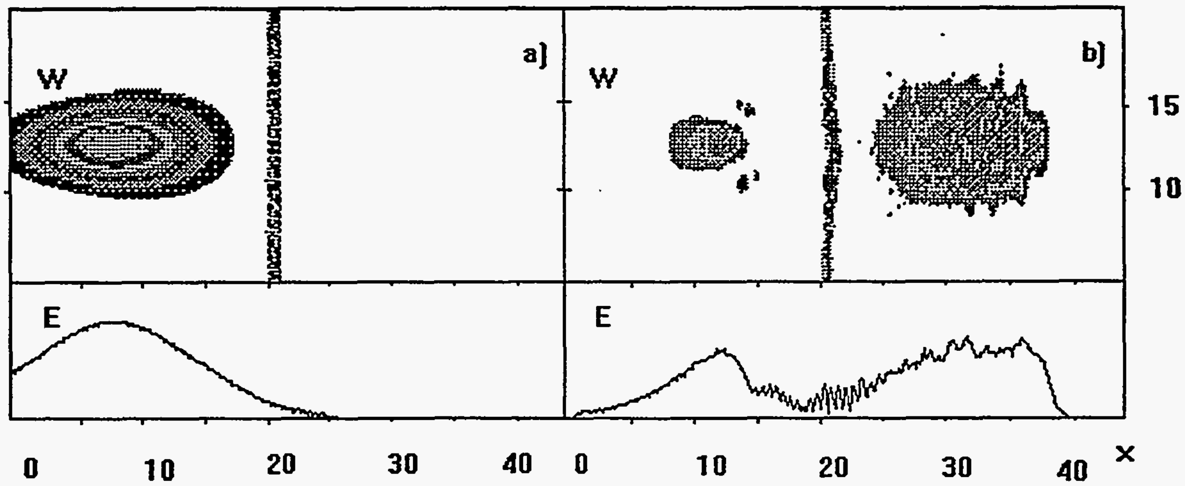

FIG. 1. 2-D simulation of the formation of a sharp leading front in a pulse with dimensionless amplitude $a = 1$ irradiated over a thin foil where $\omega/\omega_p = 1.1$: a) pulse shape before interaction with the foil; b) transmitted pulse with a typical step-like shape.

III. CHARGED PARTICLE ACCELERATION BY WAKE FIELD

III.1. Acceleration in nonuniform plasma without phase-slippage limit

To be effectively accelerated, a charged particle must be in the proper phase of a wake plasma wave. In a plasma with uniform density, the phase velocity of the wave does not change along the propagation while the particle velocity increases in the course of the acceleration. This breaks the wave-particle resonance conditions and hence restricts the final particle energy. In nonuniform plasmas the group velocity and the amplitude of the electromagnetic wave packet depend on the coordinate along the way of the pulse propagation, and thus the plasma wake wave phase velocity and amplitude vary. With an appropriate choice of the plasma density profile one can enlarge the acceleration length [9,10] considerably. The solution of this problem gives an example of the application of well known phase stability principle by V. I. Veksler and E. McMillan to the problems of charged particle acceleration by laser radiation.

The equations of the electron motion in the electric field of a one dimensional wake plasma wave can be written in the form

$$\frac{d}{dx}\left(\frac{\psi}{\omega_p}\right)=\frac{\left(m^2c^2+p^2\right)^{1/2}-p}{cp}-\frac{\omega_p^{\ 2}}{2\omega^2c}, \qquad (1)$$

$$\frac{d}{dx}\left(m^2c^4+p^2c^2\right)^{1/2}=-eE, \qquad (2)$$

where

$$\psi = \omega_p(t - t_0) = \omega_p\left(t - \int_0^x \frac{dx'}{v_g}\right) \tag{3}$$

is the wave phase, t_0 is the time at which the pulse reaches the point x, p is the particle momentum, and E is the wake field.

The electric field depends on the coordinate x and the phase ψ. In a uniform plasma, an ultrarelativistic particle in a moderately strong plasma wave acquires an energy of the order of $\Delta E \approx eE_m l_{acc}$, with l_{acc} the acceleration length which is given by $l_{acc} \approx (2c/\omega_p)\gamma_{ph}^2 = c/\pi\omega_p(\omega/\omega_p)^2$ [3,11]. This length is larger than the plasma wave length by the factor $(\omega/\omega_p)^2$. In an inhomogeneous plasma with a density that depends on the coordinate as $n(x) = n_0(L/x)^{2/3}$, with $L \approx (c/3\omega_p)(\omega/\omega_p)^2$, a laser pulse with moderate amplitude, $a < 1$, and length l_p excites a wake plasma wave with electric field $E(x,t) = -\omega_p^2(x)(ml_p a^2/4e)\cos\psi$. In this wave the acceleration length becomes formally infinite and the particle energy growth is unlimited

$$E(x) \approx mc^2\left(\frac{\omega}{\omega_p}\right)^2\left(\frac{x}{L}\right)^{1/3}. \tag{4}$$

III.2. Acceleration of charged particles at the wave-breaking regime

A second possibility of enhancing the efficiency of the acceleration of charged particles is to increase the value of the electric field in a nonstationary plasma wave.

In the course of the laser pulse propagation in an underdense plasmas, if the pulse scale nonuniformity is shorter than λ_p for nonrelativistic amplitude, $a < 1$, and shorter than λ_p/a for $a > 1$, the amplitude of the wake field produced behind the pulse corresponds to the maximum value of the electrostatic potential $\varphi_m = (mc^2/2e)a^2$. Taking into account the relativistic dependence of the relativistic Langmuir wave frequency on the wave amplitude [12], the longitudinal component of the electric field in the wake is equal to $E_m \approx (m\omega_p c/e)a^2$ when $a < 1$, and $E_m \approx (m\omega_p c/e)a$ when $a > 1$, respectively.

As was demonstrated in [12,13] the maximum field in a stationary plasma wave is given by $eE_m/mc\omega_p = (2(\gamma_{ph} - 1))^{1/2}$, where $\gamma_{ph} = (1 - \beta_{ph}^2)^{-1/2}$. For larger values of the electric field, the wave breaks and its structure becomes distorted and transient in time. However the region where the wave has a regular structure can exist for a rather long time due to the relatively low value of the velocity with that this region propagates in the frame comoving with the laser pulse. An estimate of the maximum wake field amplitude can be obtained by requiring that no wave-breaking occurs inside the laser pulse before the electrostatic potential in the pulse reaches its maximum amplitude. In the pulse the electrons of the background plasma are accelerated in the direction of the pulse motion up to the velocity $v_e \approx c(1 - 2/a^2)$. Thus the requirement $v_e < v_{ph}$ gives the maximum value of the laser pulse amplitude $a < 2\gamma_{ph} = 2(1 - \beta_{ph}^2)^{-1/2}$. When this condition is satisfied, background electrons inside the pulse are not trapped in the plasma wave. Then, in the case of a long pulse, the maximum value of the electric field in the wake behind the pulse is given by [14]

$$\frac{eE_m}{mc\omega_p} = \gamma_{ph} = \frac{1}{(1 - \beta_{ph}^2)^{1/2}}, \tag{5}$$

which is much bigger than the value in the case of stationary plasma wake waves.

The particle energy gain in a plasma wave in a uniform background plasma is given by $\Delta E \approx \varphi_m \gamma_{ph}^2$. For a stationary plasma wave φ_m cannot be greater than γ_{ph} [12], so that ΔE is bounded by γ_{ph}^3. In a breaking wave instead, can be of order γ_{ph}^4.

IV. SIMULATIONS WITH DIFFERENT PULSE PROFILES

To address this problem we made use of numerical simulations with a 1-D Particle in Cell (PIC) code. In this code, physical variables depend on x only and a $1000\delta x$ grid is used with approximately 10^5 particles.

In order to compare the particle acceleration gain, we performed 1D PIC simulations of the interaction with a uniform plasma ($n_0 = 0.004\ n_{cr}$) of two triangular pulses with length 40λ, one with a sharp rise (Fig.2) and one with a sharp rear edge (Fig.3).

We see that the triangular pulses excite regular plasma waves. Due to the development of the forward stimulated Raman scattering, self-modulation of the pulse amplitude takes place. The maximum of the pulse amplitude, as is seen in Fig. 2a, propagates with a velocity smaller than the linear e.m. wave group velocity. This can be explained by the local downshift of the electromagnetic wave frequency [7,15].

This frequency downshift leads to the decrease of the wave phase velocity of the wake plasma seen in Fig. 2b. Nevertheless, electrons injected into the plasma with initial temperature equal $5\ mc^2$, acquire an energy of the order of $500\text{-}600\ mc^2$.

In the first case (Fig.2) in the wake field produced by the pulse with a sharp rise, beam electrons are linearly accelerated up to the energy $400\ mc^2$ before the wake wave-breaking and up to $700\ mc^2$ after the wake wave-breaking.

In the second case (Fig.3), when the laser pulse has a sharp rear edge, the beam electrons are accelerated up to the energy $700\ mc^2$ before the wake wave-breaking and up to the energy $1200\ mc^2$ after the wave-breaking.

In a nonuniform plasma with a properly chosen plasma profile (where the Langmuir frequency depends on the coordinate as $\omega_p = \omega_{p0}(L/x)^{1/3}$, with $L=(1/3)(\omega/\omega_p)^3(c/\omega)$, the energy of accelerated particles is predicted to grow as $E=E_0(x/L)^{1/3}$. PIC simulations performed for a short pulse have demonstrated such acceleration rate (Fig.4(a)). The temporal evolution of the pulse demonstrates the pulse stability without self-modulation or significant change of the phase velocity of the wake wave.

To compare acceleration rates in nonuniform plasmas we performed PIC simulations. The pulse length is $l_p = 30\lambda$ ($l_p > \lambda_{p0}$) and it has a sharp rise ($l_r = 2\lambda$). The plasma density is equal to $\omega_p = \omega_{p0}(L/x)^{\alpha}$, with ω_{p0} corresponding to the density equal $n_0 = 0.004\ n_{cr}$ and α is a parameter.

For a plasma with increasing density, $\omega_p = \omega_{p0}(x/L)^{1/3}$, (Fig.5) the energy of the accelerated particles grows as $E=E_0(x/L)^{3/2}$. In the case of the plasma with increasing density, the pulse modulation and depletion appear earlier than in a uniform plasma. The charged particles are accelerated up the energy $300\ mc^2$ during $500\omega^{-1}$ and, after the wake wave-breaking, they acquire an energy of order $400 mc^2$.

In a plasma with the decreasing density profile with $\alpha = -1/3$ (Fig.6), the charged particles are accelerated up to the energy $900 mc^2$ at $\omega t = 200000$. In this case their energy increases as $E=E_0(x/L)^{1/2}$.

V. DISCUSSIONS

The present study is stimulated by the ongoing development at the ATF of a new high-power laser source, a 5-ps 4-TW CO_2 laser [16] that is expected to be operational in 1997.

Let us now estimate the value of achievable energy for a pulse produced by a CO_2 laser with $\lambda = 10\ \mu m$, power ≈ 4 TW, pulse length 0.15 cm, i.e., duration 5ps corresponding to $N=155$ periods, and a width 100 μm, i.e., 10λ. The maximum of the pulse amplitude corresponds to $a \approx 0.8$. In an underdense plasma with density such that $\omega/\omega_p < 15$ the pulse amplitude can increase up to a value of order of 2-3 due to relativistic self-focusing. In this regime the pulse energy is transported over several Rayleigh lengths. Efficient transport of the electromagnetic radiation can be achieved when the pulse propagates inside a narrow channel of width $R_\perp$. The plasma density inside and outside the channel corresponds to ω_{p1} and ω_{p2}($\omega_{p1} > \omega_{p2}$) respectively. In the channeling regime we have $R_\perp > c/(\omega_{p1}^2 - \omega_{p2}^2)^{1/2}$. Further we assume that

$\omega_{p1} \approx \omega_{p2} \approx \omega_p$. A laser pulse propagating inside such channel produces a wake field and the limiting value of the longitudinal electric field, corresponding to the wave break limit, is $eE_m/mc\omega_{p2} = (2(\gamma_{ph}-1))^{1/2} \approx (2\omega/(\omega_{p2}^2+(2\pi\, c/R_\perp))^{1/2} \approx (\omega/\omega_{p1})$, i.e., $eE_m/mc\omega \approx 1$. The maximum value of the electrostatic potential is $\varphi_m = (mc^2 a/e)(\omega/\omega_p)$. As a result, the maximum energy of the accelerated charged particles can be estimated as $\Delta E \approx amc^2(\omega/\omega_p)^3$. In a plasma with $(\omega/\omega_p) = 12$, the wake field produced by such pulse is $E_{max} \approx 1000mc^2 = 500MeV$.

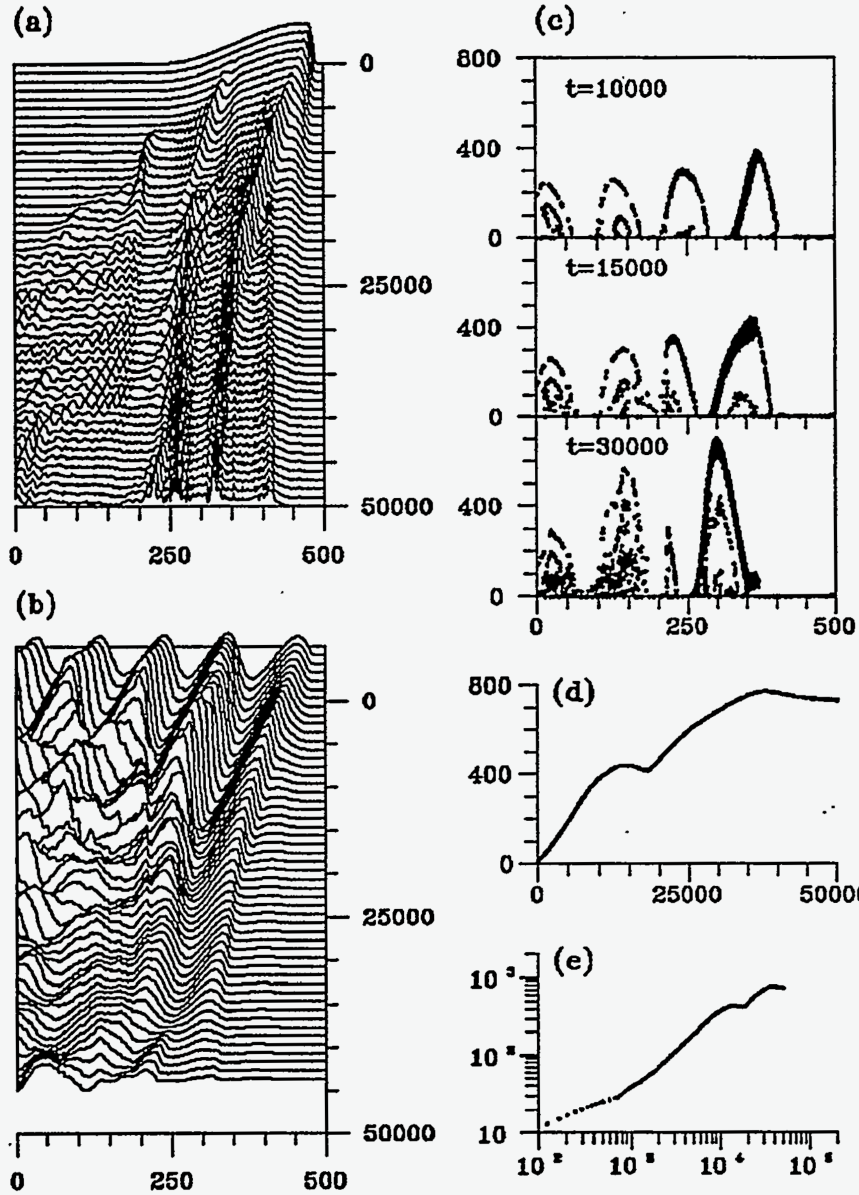

FIG. 2. 1-D simulation of the nonlinear evolution of a triangular laser pulse with sharp leading edge in an underdense plasma: a) $E_\perp$ distribution as a function of time; b) electric field in wake plasma wave; c) time evolution of the longitudinal phase plane of the beam electrons; dependence of the maximum energy of the accelerated electrons versus time in d) linear and e) logarithmic scale; (a =1, $(\omega/\omega_p)^2$=250).

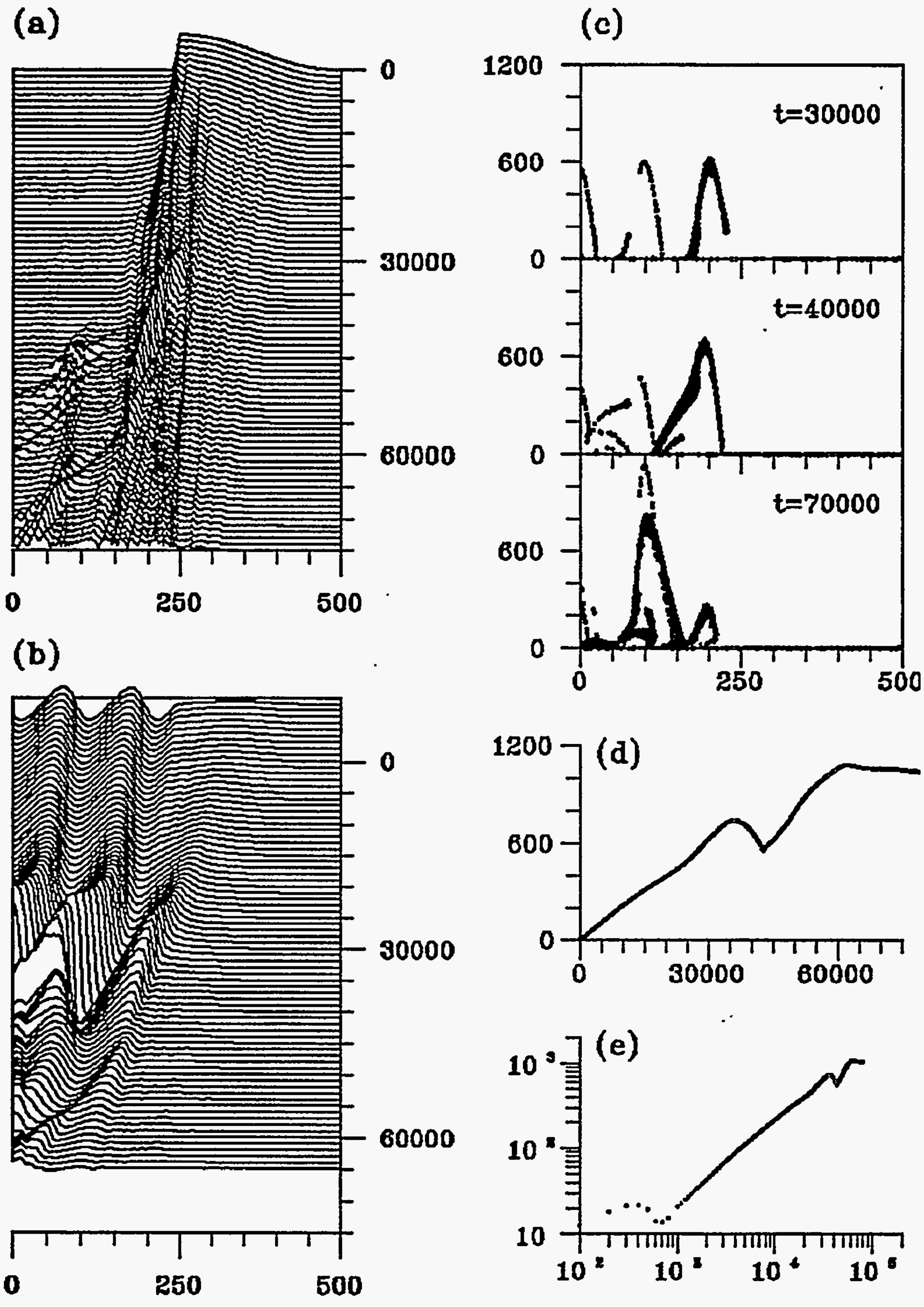

FIG. 3. 1-D simulation of the nonlinear evolution of a triangular laser pulse with sharp rear edge in an underdense plasma: a) $E_{\perp}$ distribution as a function of time; b) electric field in wake plasma wave; c) time evolution of the longitudinal phase plane of the beam electrons; dependence of the maximum energy of the accelerated electrons versus time in d) linear and e) logarithmic scale; (a =1, $(\omega/\omega_p)^2$=250).

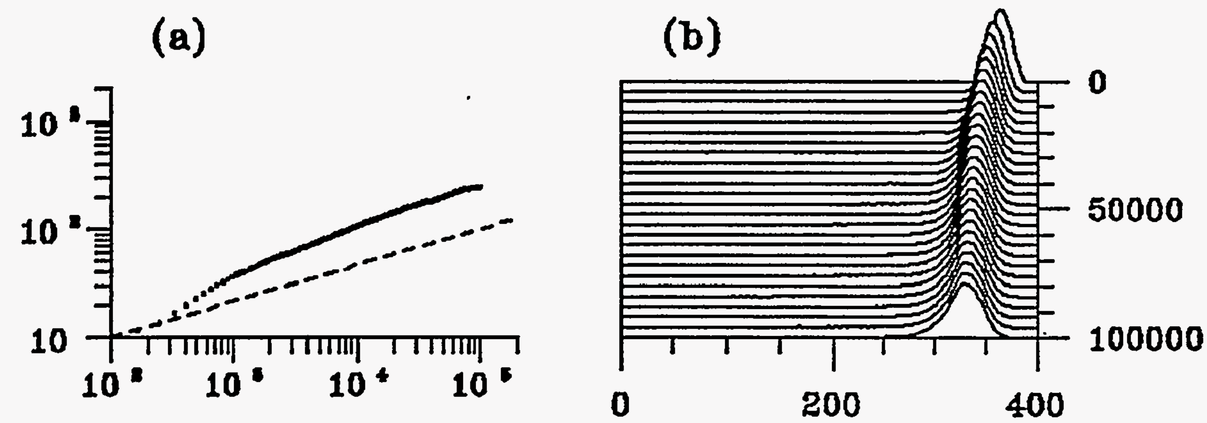

FIG. 4. The short laser pulse with the length equal 8λ propagates in the plasma with the density $n = n_0(x/L)^{-2/3}$. a) Dependence of the maximum energy of fast electrons on time and b) the evolution of the electric field in the laser pulse.

REFERENCES

[1] K. Nakajima et al., Phys. Rev. Lett. 74, 4428 (1996).
[2] A. Modena, et al. IEEE Transaction on Plasma Science 24, 289 (1996).
[3] T. Tajima, Laser and Particle Beams 3, 351 (1985).
[4] E. Esarey, and M.Piloff, Phys. Plasmas 2, 1432 (1995).
[5] S.V. Bulanov, T.Zh. Esirkepov, N.M. Naumova, F. Pegoraro, I.V. Pogorelsky, and A.M.Pukhov, IEEE Transaction on Plasma Science 24, (1996).
[6] S.V. Bulanov, F. Pegoraro, and A.M. Pukhov, Phys. Rev. Lett. 74, 710 (1995).
[7] S.V. Bulanov, I.N. Inovenkov, V.I. Kirsanov, N.M. Naumova, and A.S. Sakharov, Phys. Fluids B 4, 1935, (1992).
[8] C.D. Decker, W.B. Mori, and T. Katsouleas, Phys. Rev. E 50, R3338 (1994).
[9] T. Katsouleas, Phys. Rev. A 33, 2062 (1986).
[10] S.V. Bulanov, V.I. Kirsanov, F. Pegoraro, and A.S. Sakharov, Laser Physics 6, 1078 (1993).
[11] T. Tajima, and J.M. Dawson, Phys. Rev. Lett. 43, 262, (1979).
[12] A.I. Akhiezer, R.V. Polovin, Sov. Phys. JETP 3, 696 (1956).
[13] T. Katsouleas, W.B. Mori, Phys. Rev. Lett. 61, 90 (1988).
[14]. S.V. Bulanov, V.I. Kirsanov, and A.S. Sakharov, JETP Lett. 53, 540 (1991).
[15] S.V. Bulanov, V.I. Kirsanov, and A.S. Sakharov, Sov. J. Plasma Phys. 16, 543 (1990).
[16] I.V. Pogorelsky, W.D. Kimura, C. Fisher, F. Kannari, and N. Kurnit, in 6th Workshop on Advanced Accelerator Concepts, June 12-18, 1994, Fontana, WI, AIP Conf. Proc. 335, 405 (1995).

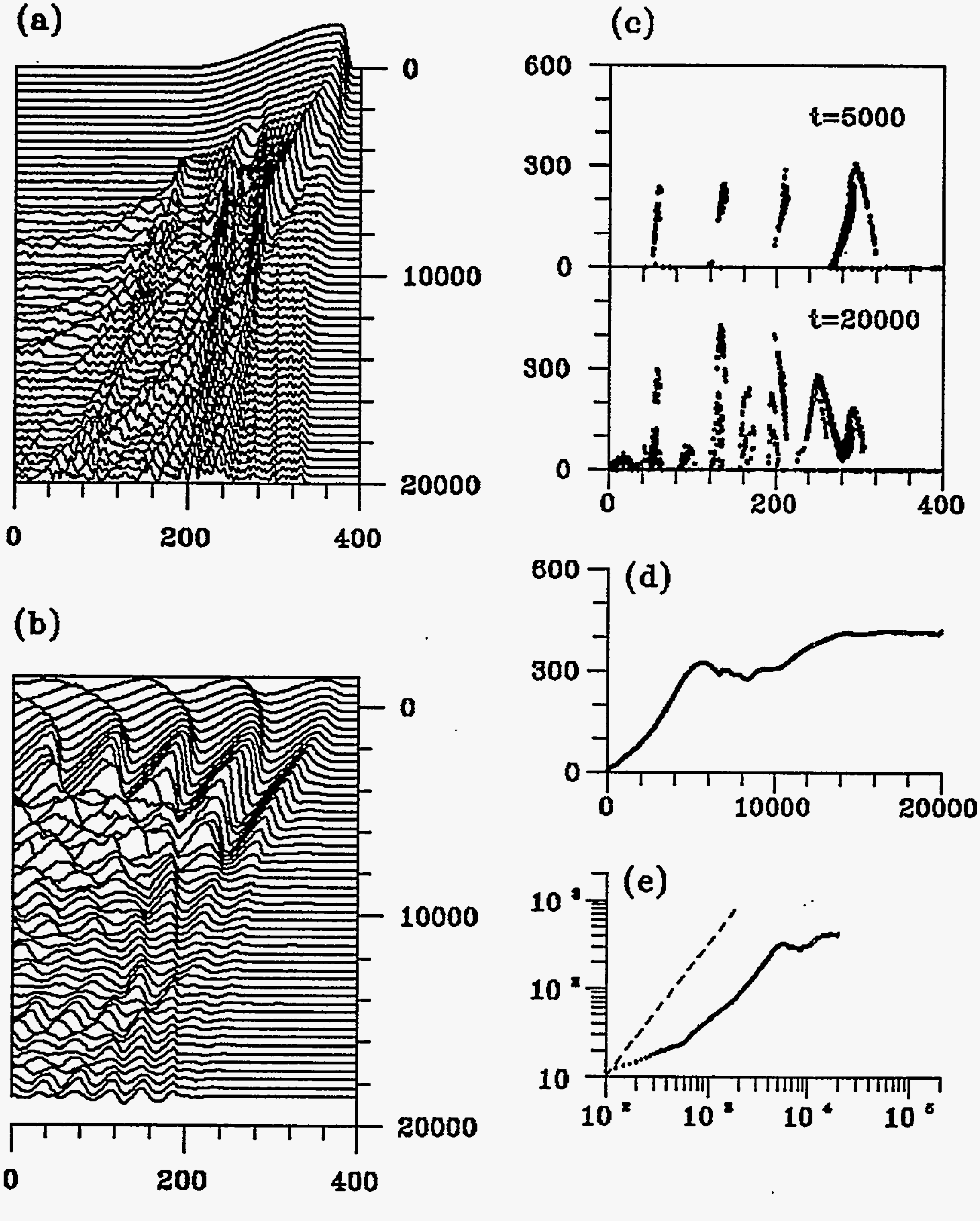

FIG. 5. 1-D simulation of the nonlinear evolution of a triangular laser pulse with sharp rise in the plasma with the density $n = n_0(x/L)^{2/3}$: a) $E_\perp$ distribution as a function of time; b) electric field in wake plasma wave; c) time evolution of the longitudinal phase plane of the beam electrons; d), e) dependence of the maximum energy of the accelerated electrons versus time, the dashed line corresponds to $y=kx^{3/2}$.

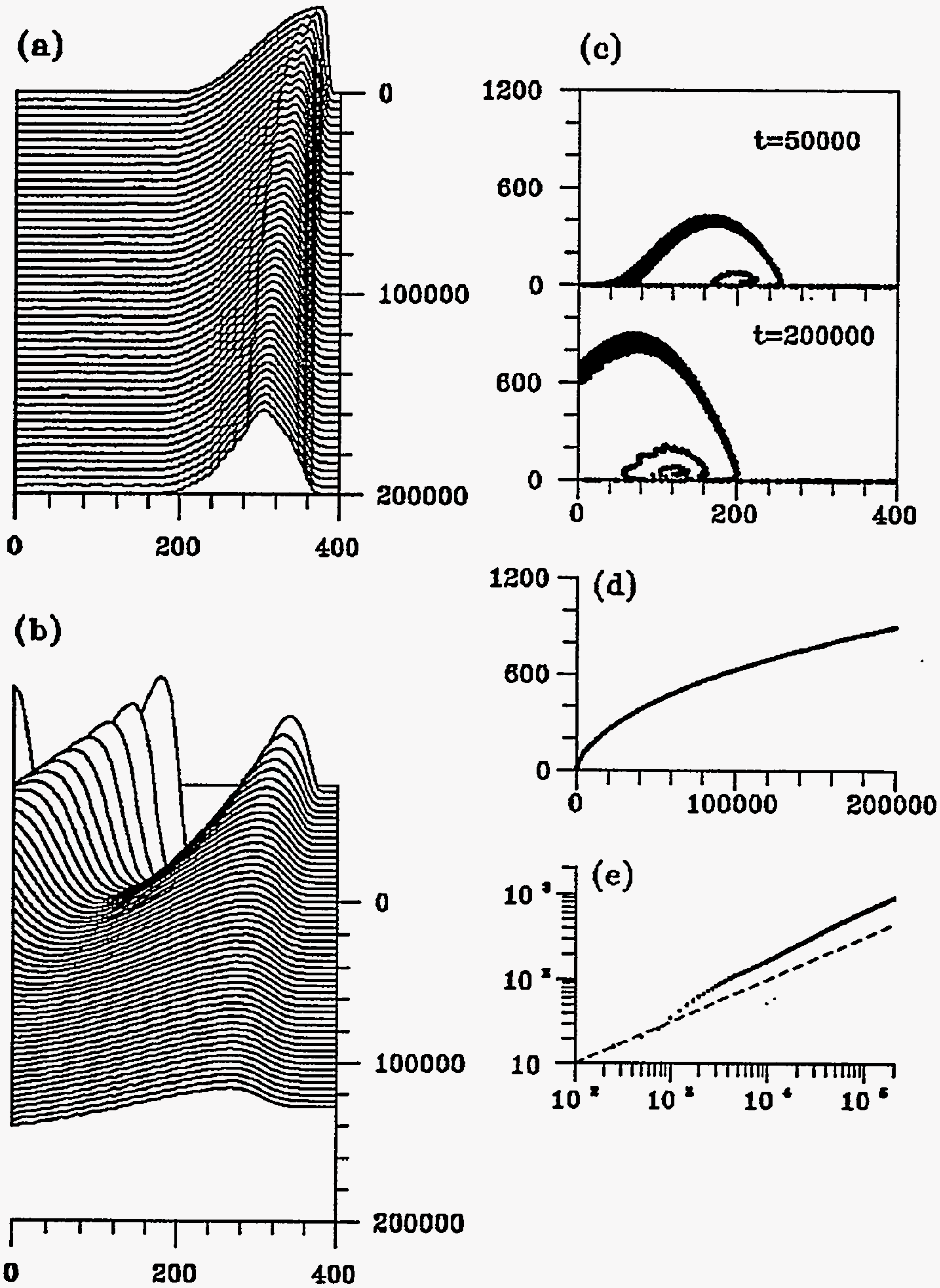

FIG. 6. 1-D simulation of the nonlinear evolution of a triangular laser pulse with sharp rise in the plasma with the density $n=n_0(x/L)^{-2/3}$: a) $E_\perp$ distribution as a function of time; b) electric field in wake plasma wave; c) time evolution of the longitudinal phase plane of the beam electrons; d), e) dependence of the maximum energy of the accelerated electrons versus time, the dashed line corresponds to $y=kx^{1/2}$.