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LASER WAKEFIELD ACCELERATION AND RELATIVISTIC OPTICAL
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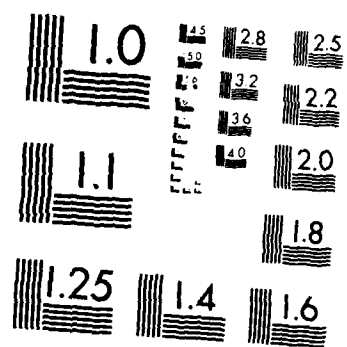
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Laser Wakefield Acceleration and Relativistic Optical Guiding

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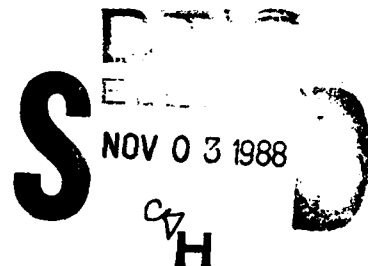
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CONTENTS

INTRODUCTION	1
OPTICAL GUIDING	3
ACCELERATION MECHANISM	5
NUMERICAL RESULTS	8
DISCUSSION	8
ACKNOWLEDGEMENTS	10
REFERENCES	11
DISTRIBUTION LIST	17



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LASER WAKEFIELD ACCELERATION AND RELATIVISTIC OPTICAL GUIDING

Introduction

It has been suggested that the next generation of high energy linear electron accelerators utilize the extremely high gradients associated with plasma waves. Excitation of plasma waves having gradients as high as several tens of GeV/m can be accomplished in a number of related ways. The plasma based acceleration schemes which have received the most attention are the plasma beat wave accelerator¹ (PBWA) and the plasma wakefield accelerator² (PWFA).

The purpose of this report is to propose a laser plasma electron acceleration scheme³ which utilizes a relativistic optical guiding mechanism. Relativistic optical guiding^{4,5} may allow a sufficiently high power laser pulse to propagate long distances within a plasma. The principle of this optically guided laser wakefield accelerator (LWFA) is that a short ($\tau_L \sim 2\pi/\omega_p \sim 1$ picosec), high power ($P \gtrsim 10^{15}$ W), single frequency laser pulse could propagate long distances in a plasma and produce accelerating wakefields in a manner analogous to that in the PWFA (see Fig. 1). In the LWFA, however, the plasma responds to the ponderomotive forces of the laser pulse as opposed to the self-fields of the electron beam as in the PWFA. In addition, in the LWFA the plasma wave is not resonantly excited as it is in the PBWA. Therefore, the plasma density in the LWFA concept does not have to be finely adjusted to achieve large amplitude accelerating fields. The idea of generating a plasma wave using a single frequency, short pulse laser was suggested by Tajima and Dawson,¹ but apparently was not pursued. More detailed consideration of the laser propagation issues, along with recent advances in laser technology, indicate that the single frequency, short pulse LWFA together with relativistic optical guiding may have advantages over the PBWA and PWFA schemes.

In the PBWA the plasma wave is excited by the beating of two relatively low power, long pulse laser beams having a frequency difference equal to the plasma frequency. The beat (ponderomotive) wave resonantly drives the plasma wave to large amplitudes. In the PWFA concept, a low energy, high current relativistic electron beam (driver) having an appropriate current profile travels through a plasma leaving behind a large amplitude plasma wave (wakefield). The wakefield accelerates a second low current, high energy relativistic electron beam. A necessary criteria for successful operation of either the PBWA or the PWFA is that the driver, i.e., radiation or electron beam, must be capable of propagating a sufficiently long distance within the plasma.

Both the PBWA and the PWFA concepts have a number of unresolved issues. In the PBWA, these include fine tuning of the laser frequencies and plasma density to within a fraction of a percent to allow for resonant growth of the plasma wave.⁶ Also the laser beams must propagate large distances within the plasma, avoiding i) diffraction, ii) laser-plasma instabilities, iii) phase detuning between the plasma waves and the accelerated electrons, as well as iv) energy depletion of the driving laser beams.⁷ The problems regarding the PWFA involve the technology of producing a high current driving beam with a slow rise time and a very rapid fall time,⁸ of the order of picoseconds, as well as the stable propagation of such a beam over large distances within the plasma. Multiple acceleration stages, all sequentially phase synchronized, have been proposed to overcome the propagation distance limitation in both the PBWA and PWFA. Multi-staging appears to be extremely difficult from a practical point of view.

Optical Guiding

The need for optical guiding in the LWFA becomes apparent when the various limitations placed on the acceleration distance are considered. One limitation on the acceleration distance is the diffraction length, L_d , which characterizes the distance over which the laser beam spreads transversely. In the absence of some form of optical guiding, the diffraction length is given by the vacuum Rayleigh length, $L_d = \pi r_L^2 / \lambda$, where r_L is the laser spot size and λ is the wavelength. Another limitation on the acceleration length is the phase detuning distance,^{1,7} $L_t \equiv 2 r_L^2 \lambda_p \approx 2(1 + \lambda_p^2 / 4 r_L^2)^{-1} (\lambda_p / \lambda)^2 \lambda_p$, where $\gamma_L^{-2} = (1 - v_g^2 / c^2)$, v_g is the group velocity of the laser pulse and λ_p is the plasma wavelength. The phase detuning length is the distance over which an ultra relativistic electron outruns the wakefield of the radiation pulse and no longer gains energy. In addition to L_d and L_t there is also the laser depletion length,⁹ $L_p \equiv E_L^2 \ell_L / E_z^2 \approx \ell_L (\ell_L / \lambda)^2 / a_{Lo}^2$, where E_L is the laser electric field, ℓ_L is the laser pulse length, E_z is the axial wake electric field and a_{Lo} is the normalized vector potential amplitude of the radiation field, $a_{Lo} = |e| A_{Lo} / (m_o c^2)$. When the pulse travels a distance L_p , the energy in the trailing plasma wakefield becomes comparable to the laser pulse energy. Typical values for L_d , L_t and L_p are ~ 1 m, ~ 100 m and ~ 1000 m respectively. In obtaining these estimates the following parameters were used: $\lambda \sim 1 \mu\text{m}$, $a_{Lo} \sim 0.5$ and $\ell_L \sim r_L \sim \lambda_p \sim 0.5$ mm. The primary limitation on the acceleration distance is due to diffraction, L_d . Clearly, some form of optical guiding within the plasma is necessary to avoid the need for multi-stage acceleration.

The optical guiding mechanism which may be appropriate for the intense, short laser pulse in the LWFA is that of relativistic guiding.^{4,5} Physically, relativistic guiding results from the quiver motion of the

plasma electrons in the radiation field, $v_q = ca_L/\gamma_L$, where $\gamma_L(r) = (1+a_L^2(r))^{1/2}$. This gives an index of refraction $n(r) = (1-(\omega_{po}^2/\omega^2)/\gamma_L(r))^{1/2}$, where ω_{po} is the ambient electron plasma frequency and ω is the laser frequency. If the radiation beam is peaked on axis, then $\partial n/\partial r < 0$, which is a necessary requirement for refractive guiding to occur. Relativistic optical guiding occurs on a fast time scale of order ω^{-1} ; hence, it can affect short pulse radiation, $\omega^{-1} \ll \ell_L/c \lesssim \omega_p^{-1}$.

Using the ray equations from geometric optics, it is possible to derive an envelope equation⁵ for the evolution of the normalized spot size $x \equiv r_L/(a_{Lo}r_{Lo})$ of the radiation beam, where r_{Lo} is the initial spot size. The envelope equation is of the form of a particle moving in an effective potential, $d^2x/dt^2 = -V_0 \partial V/\partial x$. The effective potential $V(x)$ is given by $\partial V/\partial x = -x^{-3} + 16\alpha x[g(x) - 2 \ln(g(x)/2+1)]$, where $V_0 = (2c^2/(\omega r_{Lo}^2 a_{Lo}^2))^2$, $\alpha = (\omega_{po} a_{Lo} r_{Lo}/(4c))^2$, and $g(x) = (1+x^{-2})^{1/2}-1$. Analysis⁵ indicates that the effective potential contains a minimum provided $\alpha > 1$, thus allowing for matched beam (constant spot size) solutions. Physically, α can be written, in terms of the laser power P , as $\alpha = P/P_{cr}$, where $P_{cr} \approx 17(\omega/\omega_p)^2$ GW is the critical power threshold for relativistic optical guiding. The high power levels needed for relativistic optical guiding in plasmas are consistent with the intense laser pulses needed in the LWFA.

Two points should be mentioned with regard to the propagation of finite length pulses of duration $\ell_L/c \lesssim \omega_p^{-1}$. The first is that relativistic optical guiding may also lead to "pulse clipping". That is, the front and back regions of the pulse where $P < P_{cr}$ will not be guided but instead will diffract away, leaving a shortened pulse. Only the central region of the pulse, where $P > P_{cr}$, will propagate. The second point concerns longitudinal dispersive spreading. It can be shown that

after propagating a detuning length L_t , the intrinsic frequency spread of the beam $\Delta\omega$ causes the pulse to spread by the amount $\Delta\ell_L \approx 2(\Delta\omega/\omega)\lambda_p$. Since $|\Delta\omega/\omega| \ll 1$, longitudinal dispersive spreading should not be a problem.

Acceleration Mechanism

In the relativistically guided LWFA concept the short pulse, high power laser beam provides both a radial and axial ponderomotive force on the plasma electrons. The radial ponderomotive force expels electrons radially outward while the front (back) of the laser pulse exerts a forward (backward) force on the electrons. In this sense, the laser pulse acts approximately like a negatively charged macro particle propagating through the plasma (see Fig. 1). As the plasma electrons flow around the laser pulse, large amplitude plasma waves are generated.

The ponderomotive force, exerted by the laser pulse on the plasma, moves at the pulse's group velocity and is given by $F_{\text{pond}} = |e| \nabla \Phi_L(r, z, t)$, where the ponderomotive potential is $\Phi_L \approx -m_0 c^2 a_L^2 / (2|e|)$. Note that the axial ponderomotive force from the laser pulse cannot be used directly to accelerate electrons to high energies. The ponderomotive force on the accelerated electrons is smaller than that on the plasma electrons by the factor $1/\gamma$, where γ is the relativistic factor associated with the accelerated electrons. The laser pulse must first excite a plasma wave which, in turn, can be used for acceleration. In this analysis the laser beam is assumed to be circularly polarized, although a linearly polarized laser, apart from generating harmonics, would have been equally satisfactory.

The wave equation for the plasma response or wakefield is

$$\nabla^2 \tilde{E} - \frac{1}{c^2} \frac{\partial^2 \tilde{E}}{\partial t^2} = \frac{4\pi}{c^2} \frac{\partial \tilde{J}_p}{\partial t} - 4\pi |e| \nabla \delta n_p, \quad (1)$$

where $\tilde{J}_p$ and δn_p are the plasma response electron current and number density respectively. It proves convenient to perform an algebraic transformation to the speed of light frame ($\zeta = z - ct$, $\tau = t$). The transformation should actually be to the laser pulse group velocity frame, but the differences can be neglected for the present purposes. Furthermore, a temporal steady state, $\partial/\partial\tau = 0$, in the laser pulse frame is assumed. It can be shown that for short laser pulses with $a_{Lo}^2/2 \ll 1$, the plasma quantities remain linear and nonrelativistic. The plasma, therefore, is assumed to be described by the linear, nonrelativistic, cold fluid equations. Using this fluid response, $\tilde{J}_p$ and δn_p , in the wave equation, the plasma response fields and density are given by

$$\left(\frac{\partial^2}{\partial \zeta^2} + k_p^2 \right) \tilde{E}(r, \zeta) = k_p^2 \tilde{\nabla} \phi_L(r, \zeta), \quad (2)$$

$$\left(\frac{\partial^2}{\partial \zeta^2} + k_p^2 \right) \delta n_p(r, \zeta) = - \frac{|e| n_{po}}{m_o c^2} \nabla^2 \phi_L(r, \zeta), \quad (3)$$

where $k_p = \omega_{po}/c$ and $\tilde{\nabla} = \hat{e}_r \partial/\partial r + \hat{e}_z \partial/\partial \zeta$. Note that even in the two-dimensional case the response field, $\tilde{E}$, is derivable from a scalar potential and hence, there is no response magnetic field.

From (2), the axial wakefield is given by

$$E_z(r, \zeta) = - k_p^2 \int_{\zeta}^{\infty} \cos k_p(\zeta - \zeta') \phi_L(r, \zeta') d\zeta'. \quad (4)$$

From (2) and (3) it can be shown that the transverse wakefield and plasma density are given by $\partial E_r/\partial \zeta = \partial E_z/\partial r$ and $\partial \delta n_p/\partial \zeta = -(4\pi |e|)^{-1} \nabla^2 E_z$.

As an illustration, consider a laser pulse profile of the form $a_L(r, \zeta) = a_{Lo} \sin(\pi \zeta / \ell_L) \exp(-r^2 / r_L^2)$ for $0 \leq \zeta \leq \ell_L$ and 0 otherwise. Then the axial wakefield and response plasma density within the laser pulse, $0 \leq \zeta \leq \ell_L$, and behind the pulse, $\zeta \leq 0$, are given by

$$E_z(\zeta, r) = - \frac{2\pi^2 k_p \phi_{Lo}(r)}{4\pi^2 - k_p^2 \ell_L^2} \left[\sin k_p \ell_L (1 - \tilde{\zeta}) + h \sin(k_p \ell_L \tilde{\zeta} / h) \right], \quad (5)$$

and

$$\begin{aligned} \frac{\delta n_p(z)}{n_{po}} = & - \frac{2|e|}{m_o c^2} \frac{\pi^2 \phi_{Lo}(r)}{(4\pi^2 - k_p^2 \ell_L^2)} \left\{ \cos k_p \ell_L (1 - \tilde{\zeta}) - \cos(k_p \ell_L \tilde{\zeta} / h) \right. \\ & \left. + \frac{8}{k_p^2 r_L^2} \left(1 - \frac{2r^2}{r_L^2} \right) \left[\cos k_p \ell_L (1 - \tilde{\zeta}) - 1 - h^2 (\cos(k_p \ell_L \tilde{\zeta} / h) - 1) \right] \right\}, \quad (6) \end{aligned}$$

where $\tilde{\zeta} = \zeta / \ell_L$, $k_p = 2\pi / \lambda_p$, $\phi_{Lo}(r) = -(m_o c^2 / 2 |e|) a_{Lo}^2 \exp(-2r^2 / r_L^2)$ and

where $h = k_p \ell_L / 2\pi$ for $0 \leq \tilde{\zeta} \leq 1$ and $h = 1$ for $\tilde{\zeta} \leq 0$. The transverse wakefield is easily calculated from (5) by the relation $\partial E_L / \partial \zeta = \partial E_z / \partial r$. It can be shown, as is true of PWFA, that there exists a region of length $\lambda_p / 4$ in the laser pulse frame over which the accelerated electrons experience both an accelerating axial field as well as a focusing radial field.

The axial wakefield in (5) is maximum when the laser pulse length is nearly equal to the plasma wavelength, $\ell_L \approx \lambda_p$. For $\ell_L = \lambda_p$, the maximum accelerating field is approximately π times larger than the maximum ponderomotive axial field $E_{z, \max} \approx \pi E_{\text{pond}, \max} = \pi^2 \phi_{Lo} / \ell_L$. It can be shown that the maximum accelerating field is fairly insensitive to changes in the laser pulse length and/or the ambient plasma density. It should be noted that (5) and (6) also indicate that it is possible to operate the LWFA in a

"wakeless" regime (i.e., the plasma response is nonzero only within the region of the laser pulse) when $\ell_L = m\lambda_p$, where m is an integer ≥ 2 .

Numerical Results

The results for the plasma response given by (5) and (6) are plotted in Fig. 2 for the parameters $\ell_L = \lambda_p = 0.03$ cm, $a_{Lo}^2 = 0.31$ and $r_L = 0.038$ cm. The values of a_{Lo} and r_L are those required⁵ for a relativistic optical guided beam when $\alpha = P/P_{cr} = 1.2$. The axial wakefield is shown by the solid curve and the density wake is shown by the dashed curve. The maximum accelerating gradient for this example is 2.6 GeV/m. Recall that the laser pulse extends over the region $0 \leq \xi \leq 1$.

In order to further examine the principles of the LWFA, a full scale simulation was performed using the electromagnetic particle code¹⁰ FRIEZR. FRIEZR is a 2 1/2D, fully relativistic, electromagnetic PIC code for electrons with a fluid ion background. The simulation is carried out in the transformed laboratory frame of $\zeta = z - ct$. The laser field was modeled by a fixed external ponderomotive force moving at the speed of light. The resulting axial wakefield is shown in Fig. 3 for the same parameters as used in Fig. 2. The results shown in Fig. 3 are in good agreement with analytic theory.

Discussion

The above analysis indicates that the LWFA is capable of generating acceleration gradients on the order of a few GeV/m by propagating a single, short pulse, high power laser beam through a plasma. Equation (5) gives a maximum acceleration gradient of $E_{max} \approx m_0(c\pi a_{Lo})^2 / (2|e|\ell_L)$. In addition, relativistic optical guiding occurs for sufficiently high radiation powers, $P \geq P_{cr}$. If the radiation pulse is optically guided, the acceleration

distance will be limited to the phase detuning length, L_t , instead of the much shorter free space Rayleigh length, L_d . This indicates a maximum single stage energy gain of $\mathcal{E} \equiv L_t E_{\text{max}} \approx 2\alpha\lambda_p^4/(\lambda r_L)^2$, where $\alpha = P/P_{\text{cr}}$. Table 1 summarizes these results for a CO_2 , an Nd glass and a KrF laser, each of 1 psec pulse duration. In each case $\alpha = 1.2$ which implies $a_{\text{Lo}}^2 = 0.31$ and $r_L = 0.038$ cm for a matched beam propagation in the relativistic optically guided⁵ propagation mode.

The present analysis of relativistic optical guiding neglects the effects of the electron density response on the laser pulse. Such an approximation is appropriate when $\delta n_p/n_{p0} \ll a_{\text{Lo}}^2/2$. For the present analysis, however, this condition is only marginally satisfied for parameters of interest. In addition, laser-plasma instabilities^{11,12} such as the filamentation, self-modulation or Raman scattering processes have not been considered for relativistically guided short pulses. It is anticipated that by keeping the dimensions of the laser pulse small, $r_L \sim r_L \leq \lambda_p$, the effects of these instabilities may be minimized. For example, Raman scattering processes¹² occur through the development of plasma waves within the laser pulse. Since the length scale for the development of plasma waves is λ_p , such effects may be suppressed if $r_L \leq \lambda_p$. In addition, relativistic filamentation¹¹ is a result of unstable transverse modes with $k_{\perp}^{-1} > \lambda_p$. Again, this instability may be suppressed in laser pulses with $r_L \sim \lambda_p$. Furthermore, random fluctuations in the plasma density will result in spreading of the laser spot size. A more self-consistent model of relativistic optical guiding for finite pulse lengths is currently being pursued by the authors.

The LWFA may have advantages over both the PWFA and the PBWA. For example, in the PWFA, it is necessary to use a high current (tens of kA) driving electron beam with a long rise time ($\gg \omega_p^{-1}$) and a rapid fall time

$(\ll \omega_p^{-1})$.⁸ Stable propagation within a plasma of a high current electron beam which has a pulse length greater than ω_p^{-1} may be difficult. Similarly, in the PBWA, resonant amplification of the plasma wave requires that the laser beams have long pulse lengths (many plasma periods in extent). It is likely that propagation of these long pulse beams will be plagued by the usual laser-plasma instabilities. In addition, such resonant amplification requires fine tuning between the frequency differences of the two lasers and the plasma frequency.⁶ This fine tuning, which is not necessary in the LWFA, may be difficult to achieve in practice. Although the maximum gradients attainable in the LWFA may be lower than in the PBWA, the many apparent advantages (i.e., relativistic optical guiding, stability and simplicity) of using a single, intense, short pulse laser beam, makes the LWFA an attractive acceleration scheme.

Acknowledgments

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Table 1 The laser power (P), diffraction length (free space Rayleigh length, l_d), detuning length (L_t) and single stage energy gain ($\mathcal{E} = E_z L_t$) for three lasers: CO_2 , Nd glass and KrF. The parameters are chosen to correspond to a relativistic optically guided beam with $P/P_{\text{cr}} = 1.2$, $a_{\text{Lo}}^2 = 0.31$ and $r_L = 0.038$ cm. This gives an acceleration gradient of $E_z = 2.6$ GeV/m for $\ell_L = \lambda_p = 0.03$ cm.

Laser	$\lambda[\mu\text{m}]$	$P[\text{W}]$	$L_d[\text{m}]$	$L_t[\text{m}]$	$\mathcal{E}[\text{GeV}]$
CO_2	10.6	1.9×10^{13}	0.045	0.54	1.4
Nd-glass	1.06	1.9×10^{15}	0.45	54	140
KrF	0.26	3.0×10^{16}	1.8	860	2200

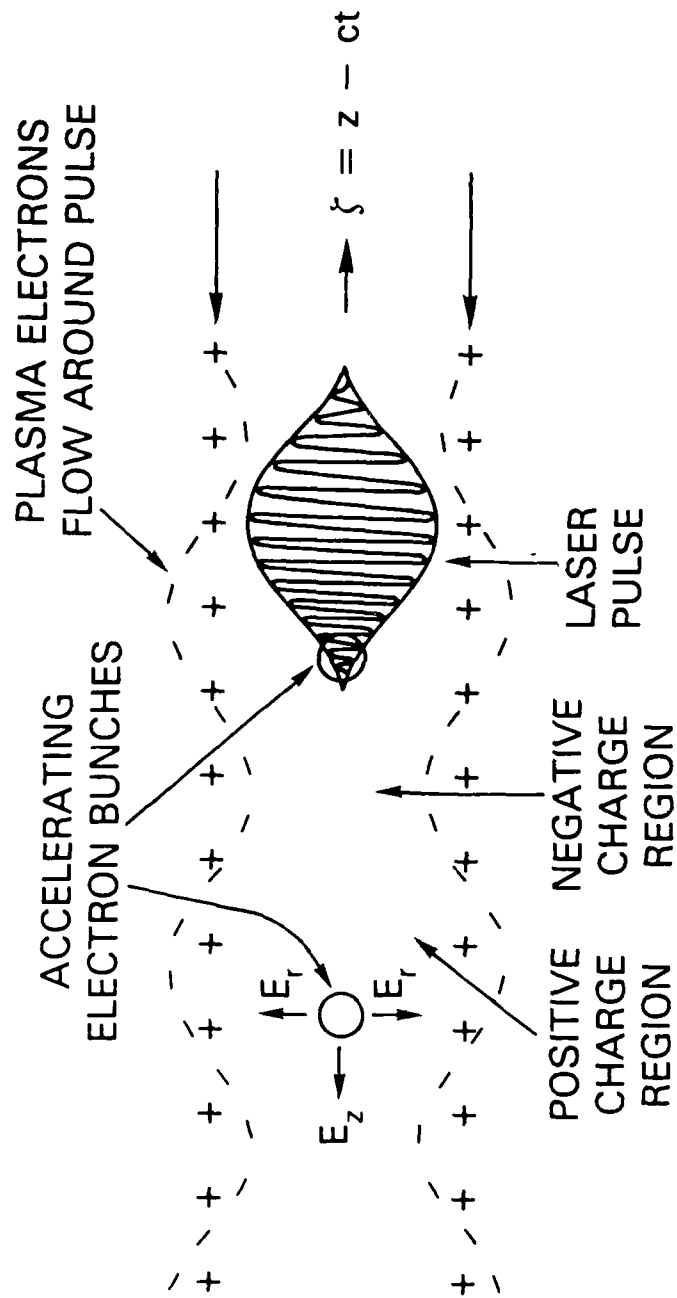


Fig. 1 Schematic of the LWFA showing the ponderomotive force from an intense short pulse laser generating a plasma wave wake as it propagates through the plasma. Roughly speaking, the laser pulse acts like an intense negative charge by repelling electrons in both the radial and axial directions.

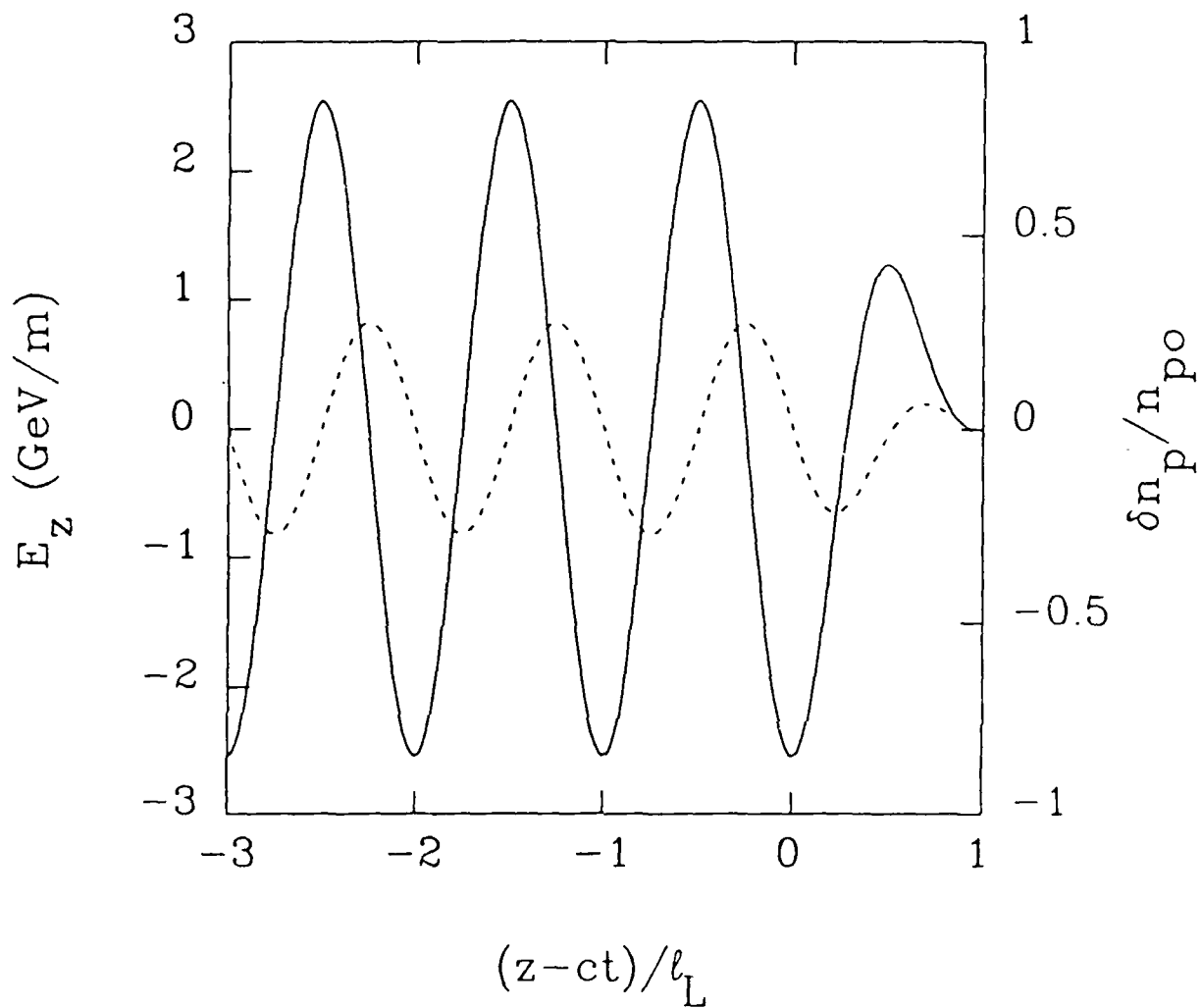


Fig. 2 The axial wakefield (solid curve) and density wake (dashed curve) for for $\ell_L = \lambda_p = 0.03$ cm, $a_{L0}^2 = 0.31$ and $r_L = 0.038$ cm. The laser pulse extends over the region $0 \leq (z-ct)/\ell_L \leq 1$.

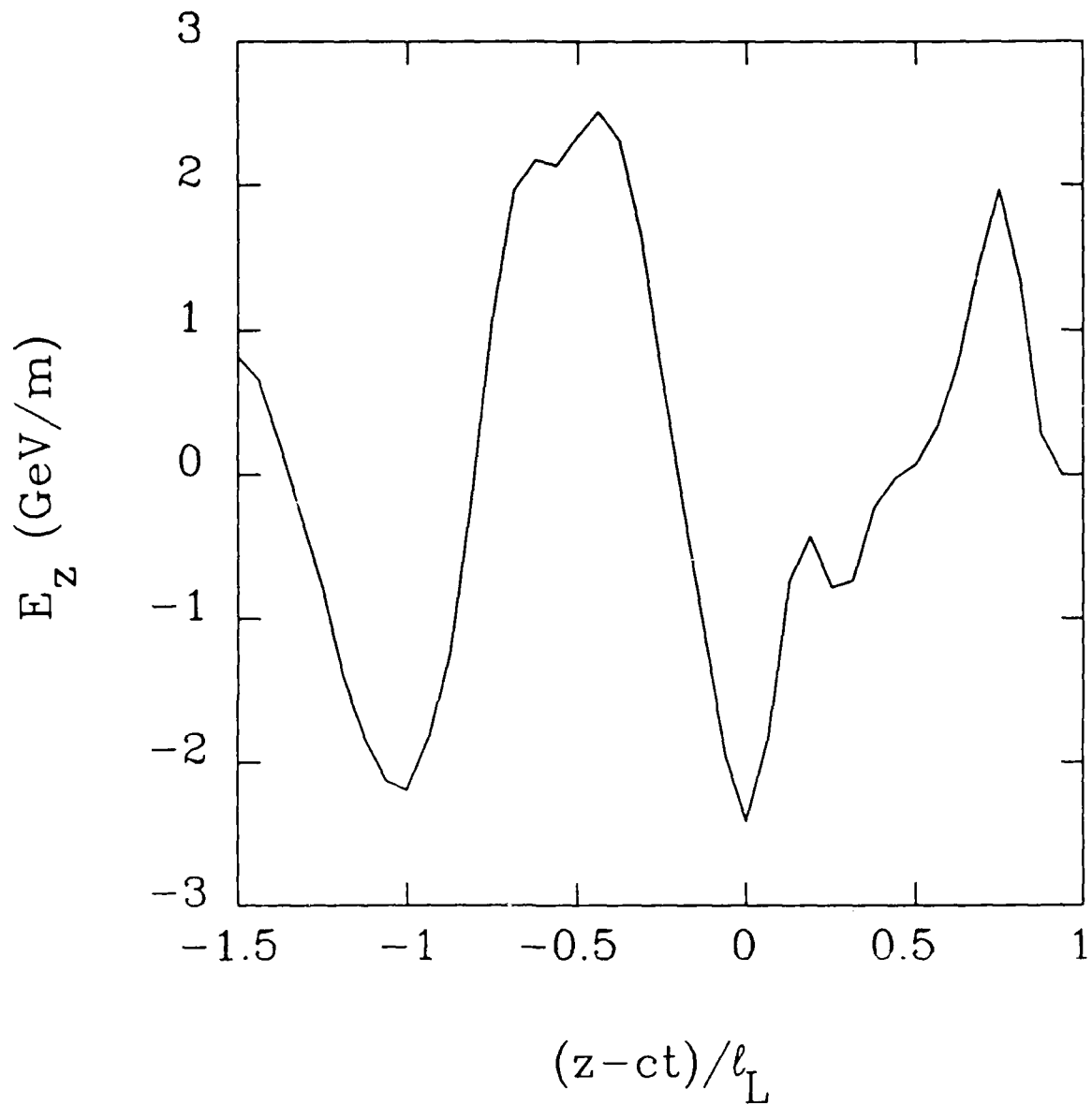


Fig. 3 The axial wakefield obtained from the particle code FRIEZR for the same parameters as in Fig. 2. The laser pulse is modeled by a fixed ponderomotive force which extends over the region $0 \leq (z-ct)/\ell_L \leq 1$.

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