J. Plasma Fusion Res. SERIES, Vol. 2 (1999) 141–144

Particle Injection into the Wave Acceleration Phase Due to Nonlinear Wake Wave-Breaking

BULANOV Sergei, NAUMOVA Nataria, PEGORARO Francesco[1] and SAKAI Jun-ichi[2]
General Physics Institute RAS, Moscow, Russia
[1]Dipartimento di Fisica, Università di Pisa and INFM, Pisa, Italy
[2]Laboratory for Plasma Astrophysics, Faculty of Engineering
Toyama University, Toyama, Japan

(Received: 10 December 1998 / Accepted: 18 February 1999)

Abstract

We discuss the wake wave-breaking that occurs due to the inhomogeneity of the Langmuir frequency with the aim of exploiting this wave-breaking to inject electrons into the acceleration phase of the wave. Particle in cell simulations show that stable beams of energetic electrons are formed. These beams are well bunched in coordinate and velocity space and contain a considerable fraction of the pulse energy.

Keywords:

high intensity laser pulses, laser wake field accelerator, injection into acceleration phase

Among the charged particle accelerators that use collective electric fields in plasmas, the Laser Wake-Field Accelerator (LWFA) provides one of the most promising approaches to high performance compact electron accelerators [1]. Acceleration of electrons in electric fields of up to 100 GV/m have been observed in LWFA experiments during the interaction of high intensity laser pulses with plasmas [2]. The production of accelerated electron beams with low energy spread requires a very precise injection of extremely short electron bunches in the appropriate phase of the wake field. We propose to use for electron injection the wake field breaking of the wake wave of a single laser pulse so as to overcome any synchronization problem [3]. Even in the 1-D case, wave breaking can either completely destroy the regular structure of the wave, or it can develop quite gently, with only a small portion of the wave involved in the break. In addition, even when the crash of the wake field occurs at the plasma-vacuum interface and destroys the wave pattern locally, nevertheless it may serve the purpose of injecting a portion of the electrons in the accelerating phase in the wake behind the laser pulse far from the plasma boundary [4]. In a homogeneous plasma the wake wave breaks, either inside the pulse or just behind it, when the square of the laser radiation amplitude a^2 exceeds γ_{ph} ($\gamma_{ph} \approx \omega/\omega_{pe}$). This regime has attracted attention since it provides both the injection of electrons into the acceleration phase and, at the same time a high rate of acceleration [5]. In this paper we present the analytical theory and the computer simulations of the nonlinear evolution of wake field waves in weakly inhomogeneous plasmas. In this case, at any given time, only a relatively small portion of the electron population is involved in the break.

In the 1-D case the Langmuir wave break occurs when the quiver velocity of electrons, v, becomes equal to the phase velocity of the wave. In a plasma with inhomogeneous density, the Langmuir wave wavenumber depends on time through the well known relationship $\partial_t k = -\partial_x \omega$. The resulting growth over time of the wavenumber results in the break of the wave even when the initial wave amplitude is below the wave break threshold. In this case the wave break occurs in such a way that only a relatively small part of the wave is involved. We can use this property to perform a gentle injection of electrons into the acceleration phase. We notice that the dependence of the Langmuir wave frequency on the coordinate may also be due to relativistic effects that cause the wake wave amplitude to vary [6]. This appears naturally due to the laser pulse depletion as it is accompanied by the downshifting of the laser pulse frequency [7], which in turn changes the wake field amplitude excited by the laser pulse. In order to describe the wake wave pattern in the region of plasma inhomogeneity, we assume the plasma frequency to vary between the two values ω_{p1} and ω_{p2} with a dependence on the Lagrange coordinate x_0 of the form $\omega_{pe}(x_0) = 0.5(\omega_{p1} + \omega_{p2}) - 0.5(\omega_{p1} + \omega_{p2}) \tanh x_0/L_1$, with L_1 the width of the region where the plasma is inhomogeneous. The resulting wave pattern in the x, t plane is shown in Fig. 1a, where the longitudinal electric field in the wake wave is shown in the frame moving with the laser pulse. We see that, behind and ahead of the region where the Langmuir frequency is inhomogeneous, the wavelength of the wake field does not depend on time, while in the inhomogeneous region the local value of the wavelength of the wake field decreases with time. In Fig. 1b the dependence of the Jacobian of the transformation from the Euler to the Lagrange coordinate and of the phase velocity of the wave $v_{ph}(x_0, t) = \omega/k$, on the Lagrange coordinate is shown. In Fig. 1c the electron velocity in the wave is plotted as a function of the Euler coordinate at the breaking time $t_{break} \approx 2L/\xi_m \Delta\omega_{pe}$. We see that in the region where the wake field frequency is inhomogeneous, the wake phase velocity decreases until it becomes equal to the quiver velocity of the electrons. Since the parameters of the nonlinear Langmuir wave approach the wavebreaking limit gradually, the wave pattern in phase plane (p, x) acquires specific features. The characteristic cusp like pattern $p' \propto x'^{2/3}$ [3] appears in the phase plane.

As the result of the break, fast electrons from the wave crest are trapped by the wave and are preaccelerated into the region where the phase velocity increases and the wake field has a regular and steady structure. In this way we obtain a gentle injection of electrons into the acceleration phase in the wake far from the breaking region. The breaking leads to the local decay of the wake wave. Its energy is transported

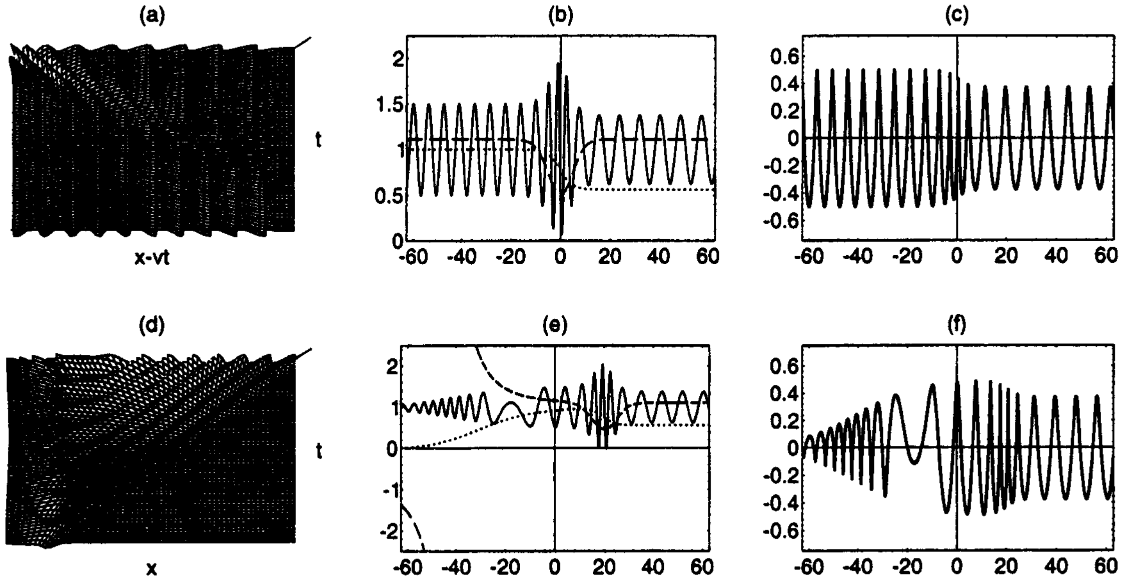

Fig. 1 a) Pattern of the electric field in the wake wave in the $x - v_g t$, t plane. b) Plasma density distribution (dotted line), dependence of the Jacobian (solid line) and of the wave phase velocity (dashed line) on the Lagrange coordinate. c) Electron momentum versus the Euler coordinate in the breaking wave. d) Pattern of the electric field in the wake wave in the x, t plane. e-f) The same quantities as in frames (b-c) in the case when the plasma-vacuum interface is taken into account.

away by the fast electrons. From the energy balance we estimate the fast electron density in the breaking region to be equal to $n_{inj} = n_0\xi_m/L$.

In order to study the long time evolution of the breaking wake wave we performed numerical simulations using the 1D PIC code described in Ref. [7]. In these simulations a circularly polarized laser pulse interacts with a weakly inhomogeneous plasma. The laser pulse length is 12λ, and its amplitude is $a = eE/m\omega c = 2$. The laser pulse is initiated in the vacuum region and then interacts with the plasma. Ions are assumed to be immobile. Asymptotically, as $x \to \infty$, the plasma is homogeneous with a density $n/n_{cr} = 1/625$ that corresponds to $\omega/\omega_{pe} = 25$. Below x and t are normalized to λ and $2\pi/\omega$, correspondingly. The plasma density varies smoothly from zero at $x = 32$ to $1/548n_{cr}$ at $x = 96$ to avoid the distortion of the plasma wave due to wave-break at the vacuum-plasma interface discussed in Ref. [4]. The plasma is homogeneous at $96 < x < 128$ and its density decreases gradually from $1/548n_{cr}$ to $1/625n_{cr}$ at $128 < x < 152$. To illustrate the difference in the wake field evolution that arises because of the finite width of the vacuum-plasma interface we present the electric field distribution in the plane x, t (Fig. 1 d), the Jacobian and phase velocity (Fig. 1 e) and the wake wave pattern (Fig. 1 e), for $\omega_{pe}(x_0) = ((\omega_{p1} + \omega_{p2}) - (\omega_{p1} - \omega_{p2}) \tanh (x_0/L_1)(1 + \tanh (x_0/L_2))$. In the vacuum-plasma interface we see the formation of wake breaking toward the vacuum region. This process is similar to the "electron vacuum heating" discussed in Ref. [8].

We have performed a long-time run, up to 2500 periods of the electromagnetic wave, in order to study both the injection and the subsequent acceleration of the electrons injected into the wake field. The simulations were made in a "moving window". In Fig. 2 we show the electric field in the wake obtained in the PIC simulations in the region of plasma inhomogeneity (a) in the time interval $0 < t < 280$, and behind the laser for $300 < t < 2500$ (b) where it has a regular stationary structure. In Fig. 2a we see the change of the local wavelength of the wake field in agreement with Fig. 1d. In Fig. 3 the phase plane at different times is shown. At $t = 130$ (a) we see the formation of the cusp structures that characterize the wave break and corresponds to Fig. 1e,f. At $t = 200$ (b), during the wave break, particles are injected into the accelerating phase of the wake field. Further acceleration is seen for $t = 300$ (c), and $t = 2500$ (d). At time $t = 2500$ the maximum energy of the fast particles is approximately 330 mc^2. The most energetic particles have been accelerated in the first period of the wake-wave behind the laser pulse. In Fig. 2c we notice that the amplitude of the wake wave for periods with numbers larger than 3 is much smaller than the amplitude in the first period. This is caused by the fact that the wake wave is loaded by the bunch of accelerated electrons and loses its energy. Thus in the regime presented in Figs. 2-3 a significant portion of the energy of the laser pulse is converted into the energy of fast particles.

A very important feature of this injection regime is that it provides conditions when the resonant wave-particle interaction in the region of homogeneous plasma forms electron bunches that are well localized both along the x-coordinate and in energy space (Fig. 4).

The main goal of LWF accelerators is to reach the largest possible accelerating field which is limited by the wake wave-breaking constraint. In a smoothly inhomogeneous plasma (and/or when the amplitude of

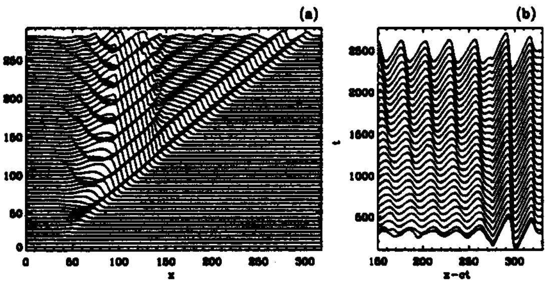

Fig. 2 The electric field in the wake wave in the x, t plane: a) in the region of plasma inhomogeneity, b) behind the laser pulse.

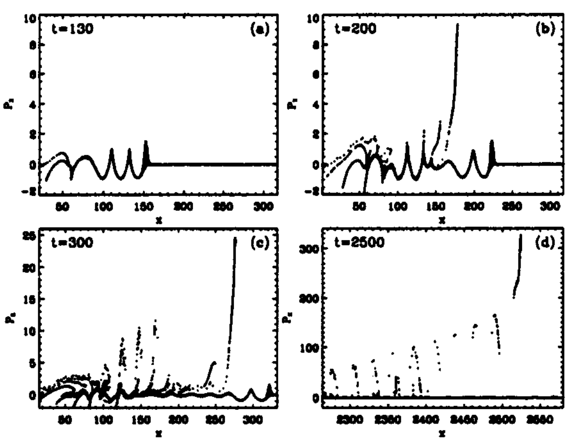

Fig. 3 Electron phase plane at $t = 130$ (a), $t = 200$ (b), $t = 300$ (c) and $t = 2500$ (d).

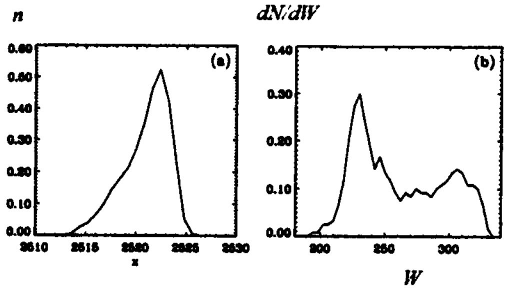

Fig. 4 Distribution function inside the bunch of accelerated electrons versus (a) particle position and (b) particle energy.

the wake depends on the coordinates) the wavelength of a relativistically strong Langmuir wave depends on time. When this wavelength becomes of the order of the quiver amplitude of the electrons, the wake starts to break. This provides a mechanism for the injection of electrons into the acceleration phase of the wake field. In this regime of injection the resonant wave-particle interaction in the region of homogeneous plasma forms electron bunches well localized both along the x-coordinate and in energy space. These bunches are stable and contain a finite portion of the laser pulse energy.

References

[1] T. Tajima and J. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

[2] K. Nakajima *et al.*, Phys. Rev. Lett. **74**, 4428 (1995); C. Coverdale *et al.*, Phys. Rev. Lett. **74**, 4659 (1995); A. Modena *et al.*, Nature **377**, 606 (1995).

[3] S.V. Bulanov, N.M. Naumova, F. Pegoraro and J.-I. Sakai, Phys. Rev. E **58**, 5257 (1998).

[4] S.V. Bulanov *et al.*, Sov. J. Plasma Phys. **16**, 444 (1990).

[5] S.V. Bulanov, V.I. Kirsanov and A.S. Sakharov, JETP Lett. **53**, 565 (1991).

[6] J.F. Drake, Y.C. Lee, K. Nishikawa and N.L. Tsinzadze, Phys. Rev. Lett. **36**, 196 (1976).

[7] S.V. Bulanov *et al.*, Phys. Fluids B **4**, 1935 (1992).

[8] F. Brunnel, Phys. Rev. Lett. **59**, 521 (1987).