Laser wakefield accelerator in a plasma pipe with self-modulation of the laser pulse

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A new design of the plasma wakefield laser accelerator is proposed. From those previously discussed, it differs in the technique of stimulation and in maintaining of the laser pulse self-modulation. The new design makes it possible to excite intense plasma waves with high phase velocities during the time required for the electron acceleration. The numerical calculations of the parameters, typical of a number of present-day laser installations, confirm the basic ideas of the proposed acceleration configuration. © *1995 American Institute of Physics.*

Various concepts of laser accelerators in a plasma are presently under discussion and investigation as possible approaches to the development of the next generation of accelerators. The concept of the laser wakefield accelerator[1–3] is one of the most promising concepts. This concept suggests that a large-amplitude plasma wakefield wave (PWFW) is excited in a low-density plasma by a short ($\tau \leqslant 1$ ps) powerful ($W > 10^{12}$ W) laser pulse. Electrons are captured and accelerated by the PWFW electric field. Recent numerical simulations[4–7] showed that the PWFW amplitude can be enlarged sufficiently by the resonant self-modulation of the pulse. Such a modulation can be obtained, on the one hand, when the longitudinal size of the laser pulse L is about several plasma wavelengths ($\lambda_p = 2\pi c/\omega_p$) and, on the other, when the peak laser power is equal to about the threshold power of the relativistic self-focusing, $P_{cr} \geqslant 16.2\ (\lambda_p/\lambda_0)^2 10^9$ W, where λ_0 is the wavelength of the laser radiation. For the existing laser technology,[8] these two conditions can be satisfied only in an adequately dense plasma, where the relativistic factor $\gamma = \lambda_p/\lambda_0$, which characterizes the phase velocity of the excited PWFW, is 10–30. This corresponds to a fairly moderate energy of the electrons captured by the wave (5–15 MeV) and imposes a constraint on the maximum energy of these electrons (less than 50–500 MeV).

For a laser pulse with a peak power lower than P_{cr} we propose another concept of triggering the laser pulse self-modulation and maintaining the propagation of the self-modulated pulse over a large distance. This approach makes it possible, using the present-day lasers, to excite the PWFW of a large amplitude and to accelerate electrons to higher energies.

1. The initial stage of laser pulse self-modulation can be treated as an instability with a simultaneous growth of the electron density perturbations and those of the radiation

intensity with a modulation period[9–13] λ_p. For a sufficiently smooth and long ($L>\lambda_p$) pulse[2,10] the plasma wave excited by a laser field, which acts as a seed-perturbation for the instability, has a fairly small amplitude.

In the simulations[4–7] the growth of the seed perturbations and triggering the instability onset are related to the relativistic self-focusing effect. In the course of the pulse propagation, the intense, central part of the pulse is compressed, while the leading edge and the trailing edge of the pulse spread due to the linear diffraction. The longitudinal pulse shape evolves in such a way that the characteristic scale of the intensity variations decreases. With a decrease in this scale, the amplitude of the plasma wave excited by the leading edge of the pulse decreases and the instability is triggered. The possibility of initiating the instability by using pulses with a sharp leading edge was discussed in Ref. 13.

In this paper we propose another way of triggering the resonant modulation instability. We suggest the use, in addition to the main pulse, other frequency-shifted (to ω_p with respect to the frequency ω_0 of the main pulse) low-intensity pulse. The beats of the laser field produced in the region occupied by the main pulse excite a plasma wave which acts as a seed for the resonant modulational instability. In our case, the peak power (the energy flux along the transverse pulse cross section) can be less than P_{cr}.

In Refs. 4–7 the condition $P_0 \geqslant P_{cr}$ was set not only to initiate the self-modulation, but also to compensate for the pulse spreading due to the diffraction. Because this condition was satisfied, the intensity of the laser field was high during the time required for the modulation instability to develop.

For $P<P_c$, the relativistic self-focusing is weaker and to maintain the high intensity of the pulse we propose to use a plasma channel formed in advance (plasma pipe), which was used in another experiment[14] and which is similar to that discussed in Refs. 3 and 15 in application to the short ($L<\lambda_p$) pulse channeling.

2. To verify and prove the physical arguments advanced above, we carried out numerical simulations of the propagation for relatively long ($L>\lambda_p$) low-power ($P<P_{cr}$) pulses in a plasma channel in the presence of a second weak-intensity pulse with a shifted frequency.

The laser pulse which propagates along the Z axis is assumed to be axially symmetric. The set of coupled equations for the normalized amplitude envelope of the laser pulse, $a=eE/\omega_0 mc$, and the density perturbation, $N=\delta n/n_0$ [where n_0 is the minimum density on the axis of the channel with the parabolic radial density profile $n=n_0[1+(\rho/R_{ch})^2]$ has the form

$$\left(2i\omega_0\omega_p^{-1}\frac{\partial}{\partial\tau}+\Delta_\perp\right)a=a\left[N-\frac{1}{4}|a|^2+(\rho/R_{ch})^2\right] \tag{1}$$

$$\frac{\partial^2 N}{\partial\xi^2}-2\frac{\partial^2 N}{\partial\xi\partial\tau}+N=\frac{1}{4}\Delta|a|^2, \tag{2}$$

where $\omega_p=(4\pi e^2 n_0/m_e)^{1/2}$ ($\omega_0 \gg \omega_p$), $\tau=\omega_p t$, $\xi=\omega_p(z-ct)/c$, $\rho=\omega_p r/c$, $\Delta=(\partial^2/\partial\xi^2)+\Delta_\perp$, and $\Delta_\perp=1/\rho\,[\partial/\partial\rho(\rho\partial/\partial\rho)]$. The value R_{ch} characterizes the channel

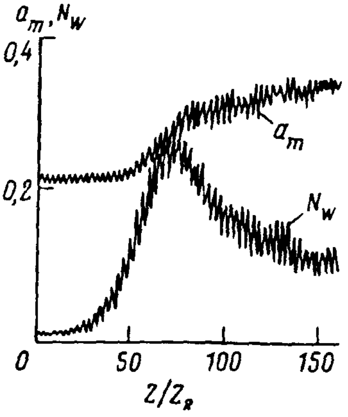

FIG. 1. PWFW amplitude, N_w, and peak amplitude of the laser field, a_m, as functions of the distance (normalized to Z/Z_R) covered by the pulse for the following values of the parameters: $a_0=0.2$, $L=40$, $L_\perp=4$, $R_{ch}=7.8$, $\gamma=50$, and $a_0/a_1=100$.

width in units of c/ω_p and is assumed to be large compared to unity. Equations (1) and (2) are valid for $|a|<1$ and $N<1$. In Refs. 4, 6, 9, and 10, the similar set were solved numerically for the case without a plasma channel.

3. As an example we consider the numerical results corresponding to the pulse that has initially the Gauss-shape profiles in both the transverse and the longitudinal directions:

$$a(\xi,t=0)=a_0 \exp[-(\xi^2/L^2+\rho^2/L_\perp^2)], \tag{3}$$

where $a_0=0.2$, $L=40$, and $L_\perp=4$. Calculations were carried out for the channel with $R_{ch}=7.8$, the peak pulse power $P_0/P_{cr}=0.025$, and $\gamma=50$.

Figure 1 shows the variation of the amplitude of the excited PWFW N_w and of the peak value of the laser field amplitude a_m as functions of the distance covered by the pulse. This distance is measured in units of the Reyleigh length, $Z/Z_R=2\pi(\omega_p/\omega_0)/L_\perp^2$. The amplitude of the second weak pulse (whose frequency is shifted to ω_p compared to

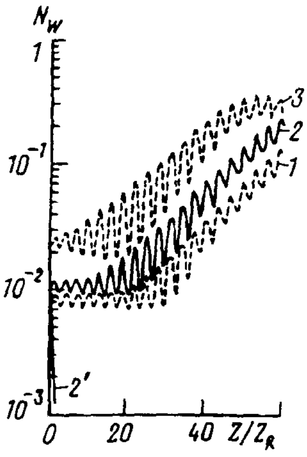

FIG. 2. Time dependences of the PWFW amplitude for three different values of the amplitude of the second frequency-shifted weak laser pulse: 1—$a_0/a_1=200$; 2—$a_0/a_1=100$; 3—$a_0/a_1=30$. The other parameters are the same as in Fig. 1. For comparison, curve 2′ represents the PWFW amplitude for the case of a homogeneous plasma (for $a_0/a_1=100$).

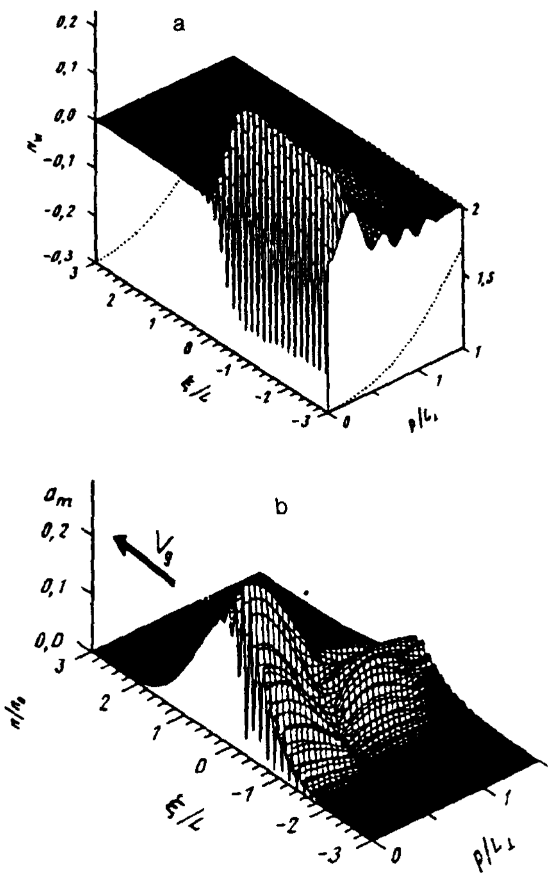

FIG. 3. Space distributions of the electron density perturbation N_w—(a) and the peak laser field amplitude a_m—(b). The plots correspond to the moment at which the PWFW with a maximum amplitude is excited (for $Z/Z_R=80$) and to the same parameters as in Fig. 1. Figure 3b shows the radial profile of the plasma density (plasma channel).

ω_p) is $a_1=a_0/100$. Fast oscillations of a_m and PWFW amplitude N_w are imposed on the more slow variations due to the pulse pulsations inside the channel. These pulsations cannot be avoided, because the nonlinearity does not allow one to obtain an ideal adjustment of the pulse and the channel in the case of the developing self-modulation. It can be seen that the PWFW amplitude (averaged over the pulsations) remains fairly large, while the pulse covers distances of several tens of Reyleigh lengths. We note that the results of our calculations do not depend on the sign of the frequency shift.

Figure 2 shows PWFW amplitude for three different values of the amplitude of the second weak pulse plotted as functions of the distance covered by the pulse. The same slopes of the curves averaged over the pulsation period indicate that the modulation of the pulse suggests an unstable behavior during the time the pulse covers sufficiently large distances. We note that the maximum level of the PWFW amplitude depends only slightly on the initial perturbation level. The limitation of the PWFW growth is related to the violation of the regular character of the laser field modulation. These irregularities, which occur first near the trailing edge of the pulse, develop and extend in the final stages to the bulk of the pulse. This disrupts the ordinary modulation of the pulse and, as a result, leads to a decrease in the PWFW amplitude. In this figure curve 2′ shows the rapidly decreasing (due to the linear diffraction spreading) PWFW amplitude in the case of a homogeneous plasma (in the absence of transverse density profiling). For a moment corresponding to excitation of the PWFW with the maximum amplitude, the plots of Fig. 3 show (a)—the space distribution of the density perturbations and (b)—the laser field amplitude. In Fig. 3a, there is also the unperturbed radial density profiles shown by the dots. The wakefield transverse size is of the order of the plasma wavelength λ_p. Figure 3b shows the development of the complex radial structure of a laser pulse, which in the course of further pulse evolution evolves into a radial ring structure.

In application to a possible experiment that uses ultrashort laser pulses with a radiation wavelength of about 1 μm (Ref. 8), the results of our calculations correspond to the pulse with an energy of about 1.2 J, a duration of 1.2 ps, initial radius of the focal spot 32 μm, and power density 4×10^{16} W/cm^2. Such a pulse, which is fairly typical of the present-day laser systems, can excited in a plasma channel with a characteristic radius of about 60 μm and on-axis density of 0.4×10^{10} cm^{-3} (which is fairly similar to that used in experiment[14] PWFW with a field of 17 GV/m. In a field of such a wakefield wave, the electrons can be accelerated from the initial energy of 25 MeV to 1 GeV over a distance of 6 cm (20 Z_R).

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