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Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (20 May 1998)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held at the P L Kapitza Institute for Physical Problems, RAS on 20 May 1998. Six papers were presented at this session:

(1) **Andreev N E** (Institute of High Temperatures, RAS, Moscow), **Gorbunov L M** (P N Lebedev Physics Institute, RAS, Moscow) "Laser-plasma acceleration of electrons";

(2) **Kim A V, Ryabikin M Yu, Sergeev A M** (Institute of Applied Physics, RAS, Nizhniĭ Novgorod) "From femtosecond to attosecond pulses";

(3) **Fedorov M V** (General Physics Institute, RAS, Moscow) "Stabilization of atoms in a strong laser field";

(4) **Andreev A A, Yashin V E** (Institute for Laser Physics, St. Petersburg), **Charukhchev A V** (Institute of Complex Testing of Optical and Electronical Systems) "Hard X-ray and fast particle generation using multiterawatt laser pulses";

(5) **Gordienko V M, Savel'ev A B** (Department of Physics and International Laser Center, M V Lomonosov Moscow State University, Moscow) "Femtosecond plasma in dense nanostructured targets: new approaches and prospects";

(6) **Babin A A, Kiselev A M, Pravdenko K I, Sergeev A M, Stepanov A N, Khazanov E A** (Institute of Applied Physics, RAS, Nizhniĭ Novgorod) "Experimental investigation of the influence of subterawatt femtosecond laser radiation on transparent insulators at axicon focusing".

An abridged version of the papers is given below.

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Laser-plasma acceleration of electrons

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1. Introduction

In recent years, considerable progress has been achieved in generation of superstrong electromagnetic fields in the optical range. It is important to emphasize that such fields can be generated by using relatively small and not very expensive setups based on T^3 (*Table Top Terawatt*) lasers. The concept of such lasers was suggested in 1985 [1] and realized in 1987 [2]. Since this concept is associated with the amplification of laser pulses whose carrier frequency continuously changes along the pulse, these lasers are also often called CPA lasers (*Chirped Pulse Amplification*). A characteristic feature of such lasers is the short pulse duration τ_L (from 1000 to 10 fs, i.e., $\tau_L = 10^{-12} - 10^{-14}$ s) and a wavelength λ_L of the order of 1 μm. At present, these lasers produce a radiation intensity of up to $I \sim 10^{20}$ W cm^{-2}, corresponding to an electric field strength in vacuum of the order of 3×10^{11} V cm^{-1}. Setups which will produce a radiation intensity above 10^{21} W cm^{-2} are at the completion stage. Note for comparison that the electric field that holds an electron near a nucleus in the hydrogen atom is 5×10^9 V cm^{-1}, whereas the momentum of a free electron moving in the field of an electromagnetic wave becomes relativistic, i.e., of the order of mc (m is the electron mass and c is the speed of light) for an electric field strength of 3.6×10^{10} V cm^{-1}.

At present T^3 lasers are used in many laboratories worldwide for studies of various processes and the development of new applications. One such application is due to the development of a new generation of small-size high-energy electron accelerators.

The dimensions of modern electron accelerators are determined by the accelerating field strength, which is about $10^7 - 10^8$ V m^{-1}, and is restricted by breakdown in the vacuum accelerating system. For this reason, the problem of particles acceleration in a plasma rather than in vacuum has been discussed for a long time [3]. In this case, on the one hand, the restriction caused by breakdown is absent and on the other hand the electric field strength in the relativistic charge density wave (whose phase velocity is close to the speed of light) can achieve huge magnitudes. Indeed, a simple estimate with the help of the Poisson equation allows one to relate this electric field strength (V cm^{-1}) to the concentration n_e (cm^{-3}) of electrons in the plasma:

$$E \cong \alpha n_e^{1/2} \,, \tag{1}$$

where $\alpha = \delta n / n_e$ is the dimensionless amplitude of the plasma wave (δn is the amplitude of oscillations of the electron density). For an electron density $n_e = 10^{17}$ cm^{-3} and $\alpha = 0.3$, the accelerating field strength in a plasma wave amounts to 10^8 V cm^{-1}, which is two – three orders of magnitude higher than that in conventional radio-frequency accelerators.

The possibility of using lasers for excitation of relativistic waves of charge density was first discussed in paper [4] where, however, the main attention was devoted to resonance excitation by means of two-frequency laser radiation of the moderate intensity. The possibility of using high-intensity short pulses from T^3 lasers for excitation of the charge-density waves (the so-called wake plasma waves) has attracted attention and been widely discussed after the publication of papers [5, 6] (see also Refs [7, 8], reviews [9, 10] and papers cited therein).

The physical mechanism of excitation of the wake waves is related to the action of the high-frequency pressure forces (ponderomotive forces) of the laser pulse on electrons in a plasma. Under the action of these forces, electrons are ejected from the region of the laser pulse, resulting in a perturbation of the electron density. The charge-separation field produces the charge-density wave behind the laser pulse, whose phase

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velocity is equal to the group velocity of the laser pulse. In a rarefied plasma, the latter is quite close to the speed of light, so that the phase velocity of the wake plasma wave is also close to the speed of light, which is required for the efficient acceleration of relativistic electrons. Recent experiments [11] showed that such a wake wave is, indeed, efficiently excited by a short laser pulse and its field is localized in the transverse direction and oscillates in the longitudinal direction, not being destroyed at a distance from the pulse of up to several tens of wavelengths, which allows one to use it for regular acceleration of electrons.

2. Laser wake-field accelerator

2.1 The general scheme and basic relations

Figure 1 shows the scheme of basic elements of one cascade of the laser wake-field accelerator (LWFA) of electrons. The plasma volume, in which a powerful short laser pulse excites the wake wave and into which bunches of accelerated electrons are injected, represents just an accelerator. One of the main parameters of the accelerator is the strength of the accelerating electric field (the acceleration rate), which is determined, according to Eqn (1), by the amplitude of the wake wave depending (for a given density of plasma) on the intensity and duration of the laser pulse. The wake plasma wave is most efficiently generated by a laser pulse whose duration τ_L is close to the half-period of the wave, i.e., when

$$c\tau_L \approx \frac{\lambda_p}{2} \cong \frac{\pi c}{\omega_p} = \frac{\pi}{k_p}\,, \tag{2}$$

where $\omega_p = (4\pi e^2 n_e/m)^{1/2}$ is the plasma frequency of electrons and k_p is the wave vector of the plasma wave. The amplitude of the linear wake wave ($\alpha < 1$) is proportional to the intensity of the laser pulse:

$$\alpha = \frac{\delta n}{n_0} \cong 0.5\frac{e\Delta\varphi}{mc^2} \cong 0.5\kappa a_0^2\,, \tag{3}$$

where $\Delta\varphi$ is the full drop of the potential in the wake wave, the coefficient κ is of the order of unity and depends on the shape of the laser pulse, whose intensity I (in W cm^{-2}) is related to the dimensionless strength of the laser field a_0 by the expression

$$a_0 = \frac{eE_L}{\omega_0 mc} = 8.6\times10^{-10}\lambda_L I^{1/2}\,, \tag{4}$$

where E_L is the amplitude of the laser field strength, ω_0 is the laser radiation frequency, and λ is the wavelength in μm. Relations (1) – (3) are written for the case of weak relativity ($a_0 < 1$, $\alpha < 1$). As we shall see below, it is this region of parameters that is of most interest for the practical aims of developing multicascade high-energy electron accelerators.

Expressions (1) and (2) show that the accelerating field strength increases with increasing plasma density and with shortening of the laser pulse exciting the wake wave. However, it should be kept in mind that in a more dense plasma the group velocity of the pulse and, hence, the phase velocity of the wake plasma wave decreases, which reduces the possible acceleration length of the relativistic electron because it leaves the accelerating phase of the wave more rapidly. We shall return to the discussion of the physical limitations of laser-plasma acceleration of electrons in Section 3.

Experiments on the laser wake-field acceleration of electrons performed to date confirm the basic regularities considered above and demonstrate the possibility of generation of superstrong accelerating plasma fields in the gigavolt range (see Table 1).

Table 1. Results of experiments on laser wake-field acceleration (LWFA) of electrons with the injection of 17-MeV electrons from a linear radio-frequency accelerator (Japan).

Experiment	I, W cm^{-2}	τ_L, ps	n_e, cm^{-3}	$\Delta\varepsilon$, MeV	E, GeV m^{-1}
KEK [12]	10^{17}	1.0	10^{15}	5	0.7
KEK [13]	10^{17}	0.1	10^{17}	300	15

2.2 Laser acceleration in the regime of self-modulated laser pulse

Studies of the nonlinear dynamics of propagation of powerful laser pulses in a rarefied plasma opened up the possibility of generating intense wake waves under conditions when the laser pulse length considerably exceeds the wavelength of the plasma wave [14 – 19]. The physical mechanism of this process is related to the laser-pulse self-modulation resulting in the modulation of the pulse intensity along the longitudinal direction on a scale close to the wavelength of the plasma wave. The self-modulation is caused by the development of the laser pulse instability, which, depending on the parameters of the plasma and laser radiation, can be related to the self-focusing of the laser pulse or to its stimulated forward

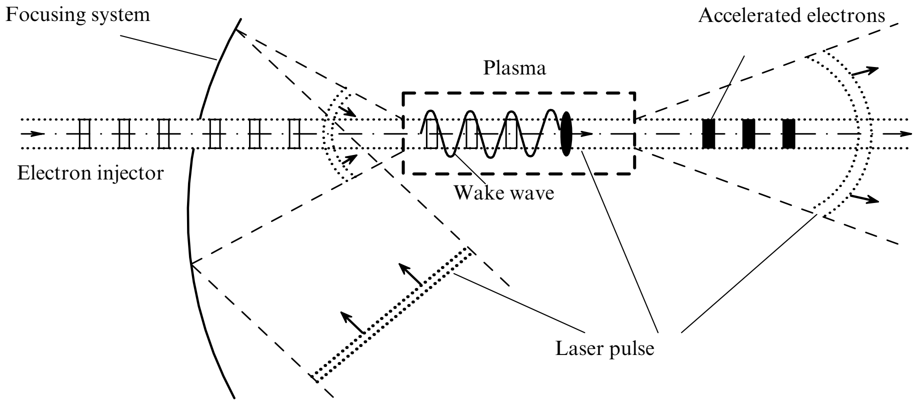

Figure 1. Scheme of one cascade of the laser wake-field accelerator.

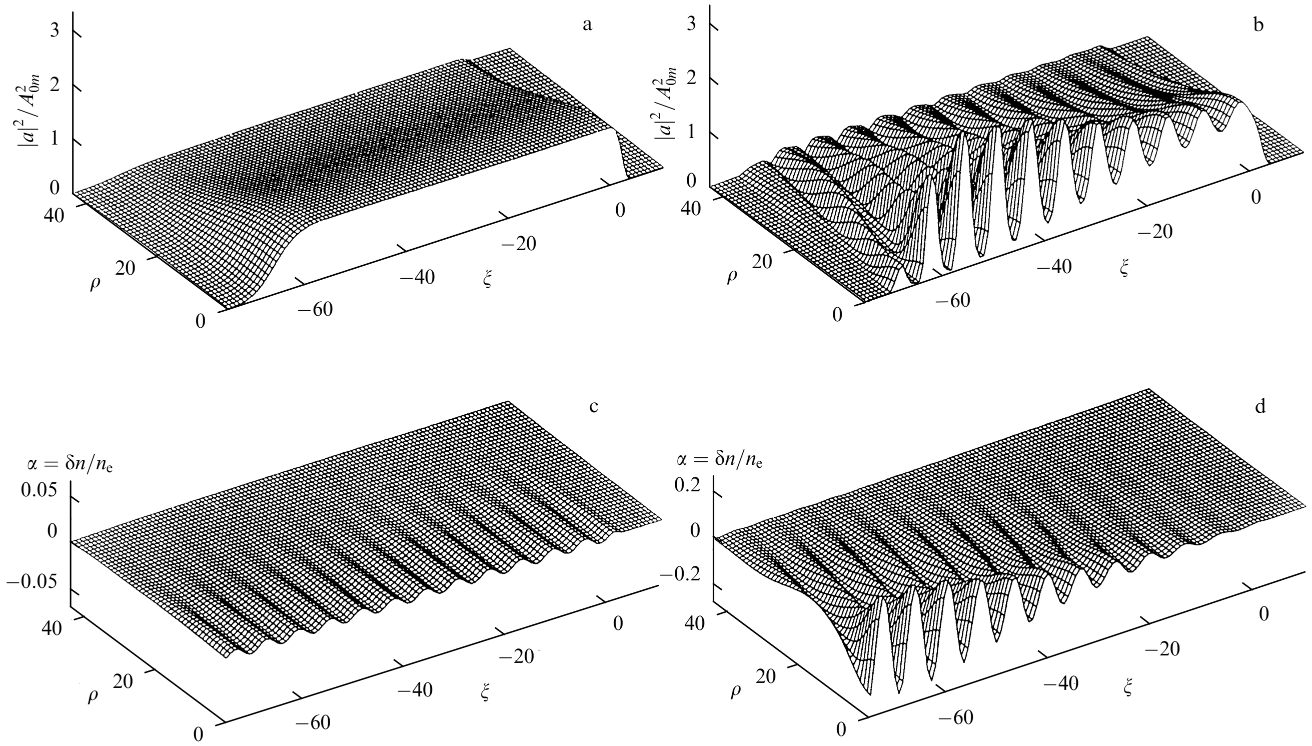

Figure 2. Spatial distributions [as functions of the accompanying coordinate $\xi = k_p(z - ct)$ and radius $\rho = k_p r$] of the normalised intensity of the laser pulse (a, b) and amplitude of the wake plasma wave (c, d) at the initial moment (a, c) and after the passage of the distance $0.6 Z_R$ by the laser pulse (b, d). The laser pulse propagates in the positive direction along the ξ-axis.

Raman scattering, and is accompanied by stimulated generation of the wake wave. Because of this, the plasma wave amplitude can substantially exceed the value determined by expression (3) for a single-frequency short laser pulse.

On the one hand, due to the development of instability, the spectrum of the modulated laser pulse becomes enriched with harmonics shifted relative to the carrier frequency by frequencies that are multiples of the plasma electron frequency, and excitation of the plasma wave becomes similar to the resonance excitation by two-frequency laser radiation, which has been discussed in the plasma beat wave acceleration (PBWA) scheme [4]. On the other hand, the generation of the plasma wave by a strongly modulated pulse can be considered as resonance excitation of the wake wave by a train of short laser pulses, the length of each of them satisfying condition (2). The generation of nonlinear wake waves with the help of a specially shaped train of short laser pulses [the so-called resonant laser plasma acceleration (RLPA) scheme] was discussed in papers [20].

It should be noted that the process of excitation of the wake wave in the regime of self-modulation mode relative to the long laser pulse has an advantage over PBWA and RLPA schemes of excitation of plasma waves, because it does not require special matching between the parameters of the plasma and laser radiation. The modulation of the laser pulse and stimulated generation of the wake wave, which appear due to instability, are self-consistent processes, which provides a large amplitude plasma wave over a comparatively broad range of the laser-plasma parameters.

For the rapid development of the instability (and propagation of the intense laser radiation through distances exceeding the Rayleigh length of the diffraction spreading of the pulse $Z_R = \pi r_L^2/\lambda_L$, where r_L is the radius of the focal spot), the laser pulse power should not be low compared to the critical power $P_c \cong 17(\omega_0/\omega_p)^2$ required for the development of relativistic self-focusing. In addition, as noted above, the pulse length should exceed the plasma wavelength $\lambda_p = 2\pi c/\omega_p$. Both these conditions are commonly satisfied at a sufficiently high plasma density, which in turn, according to Eqn (1), corresponds to high strengths of the accelerating field of the wake wave, which can be achieved in the laser-pulse self-modulation regime.

Figure 2 illustrates the results of numerical simulation of generation of the wake plasma wave in the process of self-modulation of the laser pulse during its nonlinear propagation in a homogeneous rarefied plasma. The laser pulse power in this calculation [19] was somewhat smaller than the critical one ($P = 0.68\,P_c$, the pulse length $\tau_L = 0.64$ ps, the initial radius $r_L = 100$ μm, the wavelength $\tau_L = 1.06$ μm, and the electron density in a plasma was 2×10^{18} cm^{-3}). Comparison of Figs 2c and 2d shows that the development of the laser-pulse self-modulation (see Figs 2a and 2b) results in a substantial increase (approximately by an order of magnitude) in the wake-wave amplitude.

At present, the maximum acceleration rates and maximum increase in the energy of accelerated electrons were obtained in the laser-pulse self-modulation regime [self-modulated laser wake-field acceleration (SM-LWFA)] [21–25]. Table 2 presents the main parameters of the laser pulses and plasma, as well as the results of the electron acceleration. In all these experiments except for paper [21], the accelerated electrons were not specially injected but were accelerated from a 'background' plasma. The trapping of a great number of slow electrons by the relativistic rapid plasma

Table 2. Results of experiments on laser wakefield acceleration of electrons in the laser-pulse self-modulation regime (SM-LWFA)

Experiment (country)	P, TW	I, W cm^{-2}	τ_L, ps	n_e, cm^{-3}	$\Delta\varepsilon$, MeV	E, GeV m^{-1}
KEK [21] (Japan)	3	10^{17}	1.0	10^{19}	17	30
LLNL [22] (USA)	5	10^{18}	0.6	10^{19}	2*	—
RAL [23] (Great Britain)	25	10^{19}	0.8	10^{19}	44 – 100*	100 – 200
CUOS [24] (USA)	7.5	6×10^{18}	0.4	10^{20}	> 2*	200
NRL [25] (USA)	2.5	10^{19}	0.4	10^{19}	4 – 30*	—

* Accelerated electrons from a background plasma

wave can occur upon its nonlinear breaking, when $\alpha > 1$. It is for this reason that the maximum energies of accelerated electrons and acceleration rates were achieved in experiments [23, 24], in which the laser radiation intensity was relativistic ($a_0 > 1$) and the laser pulse power was substantially greater than the critical power of the self-focusing, promoting excitation of the strongly nonlinear wake plasma wave.

Note that, although the strengths of accelerating fields achieved in experiments (~ 100 GeV m^{-1}) are by far record values, they correspond to excitation of the strongly nonlinear plasma wake wave, which loses its regularity due to breaking, and it is unlikely that it can be used for the monochromatic multicascade acceleration required for obtaining a high final energy of electrons and source brightness. For this reason, at present the use of linear or weakly nonlinear wake waves ($\alpha \leqslant 1$) appears more promising for the development of high-energy electron accelerators. The basic features of the acceleration process in these waves are considered in the next section.

3. Physical restrictions and problems of laser-plasma acceleration

The maximum energy which an electron accelerated in the wake wave of the charge density can acquire is determined not only by the acceleration rate (the strength of the accelerating plasma field) but also, obviously, by the acceleration length l_a. The acceleration length cannot exceed the distance at which a relativistic particle being accelerated (moving at the velocity that is, in fact, coincides with the speed of light c) leaves the accelerating phase of the wave (of length $\lambda_p/2$) moving at the velocity v_{ph}, i.e.,

$$l_a \leqslant L_{ph} \cong \frac{\lambda_p}{2(c - v_{ph})}\, c \cong \gamma_{ph}^2 \lambda_p \cong \gamma_{ph}^3 \lambda_L \,, \qquad (5)$$

where $\gamma_{ph} = (1 - v_{ph}^2/c^2)^{-1/2}$ is γ-factor determined by the phase velocity of the wave ($\gamma_{ph} \gg 1$), which, in the approximation of the invariable laser pulse, coincides with its group velocity; which gives, taking into account the one-dimensional linear dispersion relation for electromagnetic waves in a plasma, $\gamma_{ph} = \omega_0/\omega_p$.

The energy $\Delta\varepsilon \cong eEl_a$ acquired by the electron is maximum for the acceleration length $l_a = L_{ph}$ and is equal to

$$\Delta\varepsilon_{max} \cong eE\,L_{ph} \cong \frac{e\Delta\varphi}{\lambda_p/2} L_{ph} = 4mc^2\gamma_{ph}^2 \alpha \,. \qquad (6)$$

Note that actually the maximum energy of accelerated electrons can be approximately half of the value (6), because with the finite width of the electron bunch being accelerated, only a fraction of the accelerating phase of the wave, where radial forces affecting electrons are simultaneously focusing, can be used for regular acceleration. For example, for a linear wake wave in a homogeneous plasma, the acceleration and focusing conditions are simultaneously satisfied only for one fourth of the wave period, which reduces the maximum acceleration length (5) and, correspondingly, the maximum energy (6) by half.

Relation (6) shows that for electrons to acquire an energy of the order of several GeV in one acceleration cascade, the plasma density should be sufficiently low, so that $\gamma_{ph}^2 > 10^3$. This condition restricts, according to Eqn (1), the acceleration rate and, respectively, increases the acceleration length (5) over which electrons can gain the energy. Thus, for laser radiation with wavelength $\lambda_L \cong 1$ μm, the acceleration length $L_{ph} \cong 1$ m for $\gamma_{ph} \cong 10^2$, which corresponds to the plasma density $n_e \cong 10^{17}$ cm^{-3}, the acceleration rate $E \cong 10$ GV m^{-1} (for $\alpha \cong 0.3$), and the maximum acceleration energy $\Delta\varepsilon_{max} \cong 6$ GeV. In this case, according to Eqn (2), the duration of the laser pulse should be about 100 fs.

The main difficulty encountered in reaching these parameters is the necessity of maintaining the high intensity of the laser pulse over the long propagation length (~ 1 m), which should be of the order of 10^{18} W cm^{-2} for the example under consideration. In the absence of any mechanisms of optical channeling of laser radiation, the propagation length of the intense laser pulse (and, correspondingly, the effective acceleration length) is limited by the diffraction length $L_{diff} \cong \pi Z_R = \pi^2 r_L^2/\lambda_L$, which proves to be substantially smaller than the maximum acceleration length (5) for real parameters. Since the radiation intensity (which determines the amplitude of the wake wave) of the laser pulse of power P is inversely proportional to the square of the radius of the focal spot, the energy acquired by electrons on the acceleration length determined by the diffraction spreading of the pulse is independent of the focal spot and is limited by the value [26]

$$\Delta\varepsilon_{diff} \cong \frac{\kappa\lambda_L}{\tau_L} P \,, \qquad (7)$$

which proves to be substantially lower than 1 GeV for parameters that can be actually achieved at present ($P \sim 10$ TW, $\tau_L \sim 100$ fs, $\lambda_L \sim 1$ μm).

Optical channeling of the laser pulse to overcome the diffraction spreading is possible due to its self-focusing or creation of the plasma channel with minimum density at its axis providing the waveguide propagation of radiation. Self-focusing occurs when the pulse power exceeds the critical power $P \geqslant P_c \cong 1.7 \times 10^{-2}\gamma_{ph}^2$ TW. This restricts the plasma density by the condition $\gamma_{ph}^2 < 60P$, which, according to Eqn (6), prevents the achievement of the GeV energy range of accelerated electrons at $P < 100$ TW. For this reason at present, considerable attention is given to studies of various methods for producing plasma channels and the propagation of short powerful laser pulses in them [27 – 29], as well as to the study of the generation and structure of wake waves in channels [10, 30 – 33].

In the case of the channeled propagation of the laser pulse, the acceleration of electrons can occur over the entire dephasing length (5), and, by expressing the amplitude of the wake wave with the help of Eqns (3) and (4) in terms of the laser pulse power (and its focal spot), we obtain from Eqn (6) the following estimate of the maximum increase in the energy of electrons (in GeV):

$$\Delta\varepsilon_{\mathrm{ch}} \cong \frac{P}{(k_{\mathrm{p}} r_{\mathrm{L}})^2} \, . \tag{8}$$

At present, this estimate appears quite promising, because it shows that the energy of accelerated electrons can be increased by several GeV with the help of a terawatt laser pulse if the radius of the focal spot of the laser pulse (and thus the radius of the plasma channel) does not greatly exceed the skin length $c/\omega_{\mathrm{p}} = k_{\mathrm{p}}^{-1}$. Note, however, that upon excitation of the wake wave in a comparatively narrow plasma channel (with a radius of the order of the skin length), its structure changes as it moves away from the trailing edge of the pulse, so that the accelerating plasma field substantially decreases, whereas the radial fields increase [31–33]. This reduces the number of electron bunches which can be simultaneously accelerated by a single laser pulse.

Finally, we emphasize that none of the estimates presented above takes into account the change in the laser pulse during its propagation. In the case of the moderate relativistic intensities ($a_0 \leqslant 1$) considered above, a noticeable change in the pulse amplitude caused by transfer of the laser radiation energy to the excited wake wave occurs over a length exceeding the dephasing length (5) and, therefore, can be neglected in the first approximation. However, problems of the nonlinear dynamics of propagation of powerful short pulses in plasma channels and of the dynamics of regular low-emittance acceleration of relativistic electrons in a real nonstationary wake wave require further investigation [33].

4. Conclusions

Apart from T^3 lasers with the radiation wavelength close to 1 μm, the recent development of powerful CO_2 lasers with a wavelength of 10 μm has been reported [34]. Such lasers offer certain advantages in the application for electron acceleration. A proportional increase in the wavelength of the plasma wake wave (with the value of γ_{ph} being invariable) simplifies the requirements for the dimensions of electron bunches, which should be small compared to the wavelength of the plasma wave in order to provide a monochromatic acceleration of electrons with a small energy spread. In addition, the maximum number of electrons which can be accelerated in the wake wave, is proportional to the wavelength of the plasma wave which allows one to enhance the brightness of the source of accelerated electrons using a CO_2 laser. For this reason, despite a decrease in the acceleration rate (as compared to short-wavelength lasers) due to a decrease in the plasma density, CO_2 lasers are considered quite promising drivers for the development of multicascade laser-plasma accelerators for high-energy physics [35].

At present, several projects of laser wake-field accelerators for energies exceeding 1 GeV have been developed and are being realized (see, for example, Ref. [36]). Each of these projects contains parameters of the laser system, the electron injector, and the accelerating plasma gap. As a rule, it is assumed that the plasma channel will be used to suppress the diffraction blurring of the laser pulse.

It is expected that a successful realization of these projects will open up new prospects for multicascade compact accelerators and the achievement of higher energies of accelerated particles.

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