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# Compression and acceleration of electron bunches to high energies in the interference field of intense laser pulses with tilted amplitude fronts: concept and modelling

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***Abstract.*** **A new concept of accelerating electrons by laser radiation is proposed, namely, direct acceleration by a laser field under the conditions of interference of several relativistic-intensity laser pulses with amplitude fronts tilted by the angle 45° with respect to the phase fronts. Due to such interference the traps moving with the speed of light arise that capture the electrons, produced in the process of ionisation of low-density gas by the same laser radiation. The modelling on the basis of solving the relativistic Newton equation with the appropriate Lorenz force shows that these traps, moving in space, successively collect electrons from the target, compress the resulting electron ensemble in all directions up to the dimensions smaller than the wavelength of the laser radiation and accelerate it up to the energies of the order of a few GeV per electron.**

***Keywords:*** *high-energy electron bunches, interference fields.*

## 1. Introduction

In the last two decades, experimental and theoretical studies of interaction of relativistic-intensity laser radiation with matter have made it possible to establish a new area of modern physics, interfacial between nonlinear optics and plasma physics. One of the most important problems in this field, interesting from the point of view of both fundamental physics and solving a number of applied problems, is the acceleration of electrons up to high energies with a high-power focused laser pulses. A detailed review of the methods of electron acceleration is presented in [1–3]. In the literature most attention was paid to the mechanism of electron acceleration by the electric field of the wake wave, arising in the process of interaction between the intense laser radiation and plasma. This method is unable to provide high efficiency of the energy transfer from the laser radiation to the accelerated electrons, because only a small fraction of energy is transferred into the longitudinal electric field of the wake wave.

An alternative approach consists in direct acceleration of the electrons, injected or arising as a result of ionisation of a low-density gas target, by laser pulses. In a number of papers, including those published by the authors of the present study, the direct acceleration of electrons was modelled in the case of Gaussian pulses with relativistic intensity [4]. At the same time in [5] it was shown that one can achieve essential improvement in the energy and spatial parameters of the accelerated electron bunch by using a standing wave, produced by the interference of two counterpropagating laser pulses, each having the amplitude front tilted by a certain angle with respect to its phase front; the focal spot being strongly asymmetric. In this case, in the electromagnetic field the compression of the electron beam along one coordinate occurs up to the dimension, smaller that the wavelength of the optical field, which offers an opportunity to achieve essentially greater degree of compression, than, e.g., by electron acceleration in a wake wave.

In the present paper a new concept of direct acceleration of electrons with a high-intensity optical field is proposed, in the framework of which the accelerating standing wave is produced by the interference of several laser pulses, whose amplitude and phase fronts are propagating at a certain angle. Similar to the previous papers [4, 6], the electron dynamics is modelled by solving the relativistic Newton equation with the appropriate Lorenz force.

In accordance with the calculations presented below, in the 2D standing wave, formed by the interference of several pulses, the wave vectors of which lie in the same plane, the amplitude and phase fronts propagate at a certain angle with respect to each other, forming optical traps. The electrons of the target are sequentially captured by these traps. Due to the use of laser pulses of such configuration, the compression of the electron beam occurs in all spatial coordinates, and all captured electrons are accelerated to nearly the same kinetic energy. The modelling was performed for schemes with the interference of three (Fig. 1a) and four intense laser pulses. In the first case, it was assumed that the laser pulses converge at the angle 120° and in the second case at 90°. The amplitude fronts of the laser pulses are inclined with respect to the phase fronts by the angle $\beta$ (Fig. 1b). For the considered (currently attainable) parameters of the laser radiation the longitudinal and transverse dimensions of the electron beam as a result of interaction with the net optical field becomes smaller by three and two orders of magnitude than the wavelength, respectively, and the energy of electrons attains a few GeV.

## 2. Equations of motion

In the field of laser radiation a high-frequency Lorenz force acts on an electron, and the equation of motion takes the form:

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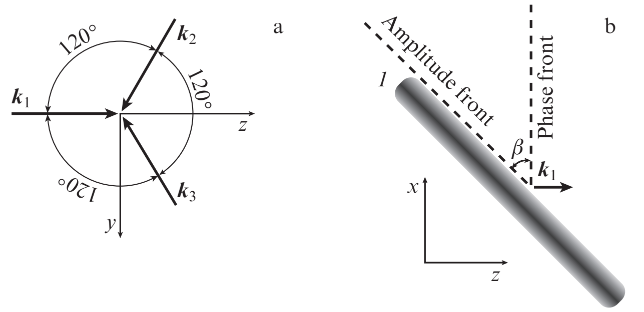


**Figure 1.** Schematic diagram of propagation of linearly polarised laser pulses. The wave vectors $\boldsymbol{k}_1$, $\boldsymbol{k}_2$, and $\boldsymbol{k}_3$ show the directions of propagation of the laser beams in the plane $(y, z)$ (a). The image of one of the laser pulses (*1*) with the tilted amplitude front ($\beta$ is the angle between the amplitude and phase fronts) (b).

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = -e\boldsymbol{E} - \frac{e}{c}[\boldsymbol{v}\boldsymbol{H}], \tag{1}$$

where $\boldsymbol{p}$ is the momentum; $\boldsymbol{E}$ and $\boldsymbol{H}$ are the strengths of the electric and magnetic fields, respectively; $e > 0$ is the absolute value of the electron charge; $\boldsymbol{v}$ is the electron velocity; and $c$ is the speed of light. Equation (1) should be completed with necessary initial conditions for the position and velocity of electron.

Equation (1) with the initial conditions is used to calculate the motion of the electron in a 2D standing wave. Below it is supposed that each of the beams, producing this wave, has two different dimensions of the waist, $\rho_{0\|}$ and $\rho_{0\perp}$, in the directions parallel and perpendicular to the direction of polarisation, respectively. The transverse distribution of the laser radiation intensity in beams is Gaussian in any cross section of the beam. In the course of the beam propagation in a certain coordinate system along the $z$ axis, the dependences of its transverse dimensions $\rho_\|$, $\rho_\perp$ on $z$ are described by the expressions

$$\rho_\|(z) = \rho_{0\|}\sqrt{1 + z^2/z^2_{R\|}}, \quad \rho_\perp(z) = \rho_{0\perp}\sqrt{1 + z^2/z^2_{R\perp}}, \tag{2}$$

where $z_{R\|} = \pi\rho^2_{0\|}/\lambda$, $z_{R\perp} = \pi\rho^2_{0\perp}/\lambda$ are the corresponding Rayleigh lengths of the beam; and $\lambda$ is the wavelength.

The structure of the electromagnetic fields for a linearly polarised beam with a Gaussian transverse distribution of intensity was studied in papers [7–9]. In the more general case of a Gaussian beam with different transverse dimensions, the expressions for the fields take the form

$$E_x = \frac{E_0(\xi)\Lambda(x,y,z)}{\left(z^2/z^2_{R\|}+1\right)^{1/4}\left(z^2/z^2_{R\perp}+1\right)^{1/4}}\sin\varphi$$

$$E_y = 0,$$

$$E_z = \frac{x}{z_{R\|}}\frac{E_0(\xi)\Lambda(x,y,z)}{\left(z^2/z^2_{R\|}+1\right)^{3/4}\left(z^2/z^2_{R\perp}+1\right)^{1/4}}\cos\tilde{\varphi}, \tag{3}$$

$$H_x = 0,$$

$$H_y = E_x,$$

$$H_z = \frac{y}{z_{R\perp}}\frac{E_0(\xi)\Lambda(x,y,z)}{\left(z^2/z^2_{R\|}+1\right)^{1/4}\left(z^2/z^2_{R\perp}+1\right)^{3/4}}\cos\tilde{\varphi},$$

where $E_0(\xi) = E_{\mathrm{m}}\exp\{-[(\xi - z_{\mathrm{d}}/c)/\tau]^{2s}\}$; $\Lambda(x, y, z) = \exp(-x^2/\rho^2_\|(z) - y^2/\rho^2_\perp(z))$; $\xi = t - z/c$; $E_{\mathrm{m}}$ is the maximal value of the field strength; $z_{\mathrm{d}}$ is the value of the initial shift of the pulse with respect to the electron position, a providing smooth rise of the field in the numerical solution; and $\tau$ is the pulse duration. The parameter $s$ determines the temporal shape of the pulse. For the Gaussian shape $s = 1$.

The phase dependence is determined by the expression

$$\varphi = 2\pi c\xi/\lambda + \frac{1}{2}\arctan\left(\frac{z}{z_{R\|}}\right) + \frac{1}{2}\arctan\left(\frac{z}{z_{R\perp}}\right)$$
$$- z\left(\frac{x^2}{z_{R\|}\rho^2_\|(z)} + \frac{y^2}{z_{R\perp}\rho^2_\perp(z)}\right) - \varphi_0,$$

where $\tilde{\varphi} = \varphi + \arctan(z/z_{R\|})$; $\varphi_0$ is the initial phase.

Equations (3) for the beam field components are derived from the asymptotic solution of Maxwell's equations in the first-order approximation with respect to the small parameter $\varepsilon = \lambda/(2\pi\rho_{0i})$ ($\rho_{0i}$ being the smallest waist radius of the beams).

In the case of a Gaussian beam, whose amplitude front is inclined with respect to the phase front by a certain angle $\beta$, the expressions of the fields are obtained by introducing the dependence of the parameter $\xi$ on $\beta$: $\xi = t - (z + x\tan\beta)/c$ (for the pulse, propagating in the positive direction of the $z$ axis, see, e.g., [10]).

The intensity of the beam is expressed as

$$I = \frac{c}{4\pi}\left|\overline{[\boldsymbol{E}(x,y,z,t)\boldsymbol{H}(x,y,z,t)]}\right|. \tag{4}$$

In the calculations for each beam the dimensionless intensity $I_{\mathrm{m}}/I_{\mathrm{rel}}$, is used, where $I_{\mathrm{m}}$ is the maximal intensity of the beam, and the relativistic intensity $I_{\mathrm{rel}}$ is defined by the expression [6]

$$I_{\mathrm{rel}} = m^2c^3\omega^2/(8\pi e^2) = 1.37\times10^{18}(1/\lambda[\mu\mathrm{m}])^2[\mathrm{W\ cm^{-2}}]. \quad (5$$

## 3. Dynamics of an electron in the field of a standing wave

In the case of inclination of the beam from the $z$ axis by an arbitrary angle in the plane $(y, z)$, the expression for the fields can be easily derived from Eqns (3) by a transformation of the coordinate system. In this case, the direction of the electric field of the laser pulse remains parallel to the $x$ axis, and the wave vector lies in the plane $(y, z)$. The results of calculating the parameters of the electron dynamics are presented below in the basic coordinate system, in which Eqns (2) and (3) were derived.

Here we present the results of calculations for Gaussian beams, as well as for beams with plane amplitude and phase fronts having different transverse dimensions, in which the amplitude front is inclined at a certain angle $\beta$ with respect to the wave front. The beams with different transverse dimensions are preferable for using in the present case, since at $\rho_\| \gg \rho_\perp$ they provide large displacements of the beam crossing area in the direction of the polarisation axis. This increases the time of interaction of the electron with the field, thereby increasing its kinetic energy.

The positions, velocities, accelerations, as well as the trajectories and various parameters of the dynamics were determined as a result of the numerical solution of Eqn (1). The calculations were performed for supershort ($c\tau/\lambda = 3.3$) pulses with Gaussian and super-Gaussian temporal ($s = 1$, $s = 2$) and Gaussian transverse profiles. It was assumed that the pulses are focused such that the transverse dimensions of the beam are $\rho_{\parallel}/\lambda = 200$ and $\rho_{\perp}/\lambda = 2.0$, and the longitudinal dimension of the caustic is much greater than the area of interaction of electrons with the field.

The motion of an individual electron in the field of a standing wave, formed by two laser pulses with plane amplitude and wave fronts, was considered in [5]. Note that in this case the electron is captured by the laser field and moves along the $x$ axis with the velocity close to the speed of light $c$.

The spatial distribution of intensity in the standing wave, produced by three or four oncoming laser pulses at $\beta = 45°$ has the form of a 3D lattice. In a small region near the $x$ axis the interference of laser beams produces traps (lattice cells), moving along the $x$ axis with the speed of light $c$.

Consider the motion of an individual electron in the field of the standing wave, formed by three Gaussian beams with tilted amplitude fronts. Figure 2 presents the 2D the trajectory of motion, the time dependence of the kinetic energy $W_k/mc^2$ and the component of the velocity along the $x$ axis at the angle $\beta = 45°$ for the laser pulses with linear polarisation and the coordinates of the initial electron displacement $x_0/\lambda = -20$, $y_0/\lambda = -0.05$, and $z_0/\lambda = -0.19$. Figure 2f shows with high magnification the time dependence of the velocity component, corresponding to the segment, selected by a dashed line in Fig. 2e. The initial position of the electron is marked with a circle in Figs 2a–c.

The motion of the electron in the field of the resulting standing wave is divided into three stages. At the first stage the electron quickly shifts to the region, adjacent to the $x$ axis. In this process the electron experiences significant acceleration, and its velocity sharply increases, approaching the speed of light $c$. Such displacement is caused by the fact that initially the laser pulses, forming the standing wave, act on the electron in an asymmetrical way, i.e., in the very beginning of the motion it is stronger affected by the pulse, towards which it is displaced initially. At the second stage the electron is captured by the laser field and moves along the $x$ axis along an almost rectilinear trajectory with the velocity, very close to the speed of light $c$. The electron slightly oscillates along the axes $z$ and $y$ (Figs 2a–b) symmetrically with respect to the $x$ axis (the scale factors are strongly different for the axes in Figs 2a and 2b). The amplitudes of the electron oscillations along the axes $z$ and $y$ differ insignificantly and depend on the initial displacement of the electron along the appropriate axis. The displacement of the electron along the $x$ axis during the time of interaction with the laser pulses greatly exceeds the amplitude of the electron oscillations along the axes $z$ and $y$. The kinetic energy of the electron smoothly increases, reaching the maximal value of $W_k/mc^2 = 6400$ (3.2 GeV) at the end of interaction with laser pulses.

Figure 3 presents the 2D trajectory of the electron motion in dimensionless coordinates ($y/\lambda$, $z/\lambda$) and the time dependence of the kinetic energy $W_k/mc^2$ at the initial electron displacement $x_0/\lambda = -10$, $y_0/\lambda = 0.7$, and $z_0/\lambda = 0.7$. Due to the change of the initial position, the trajectory of the electron in

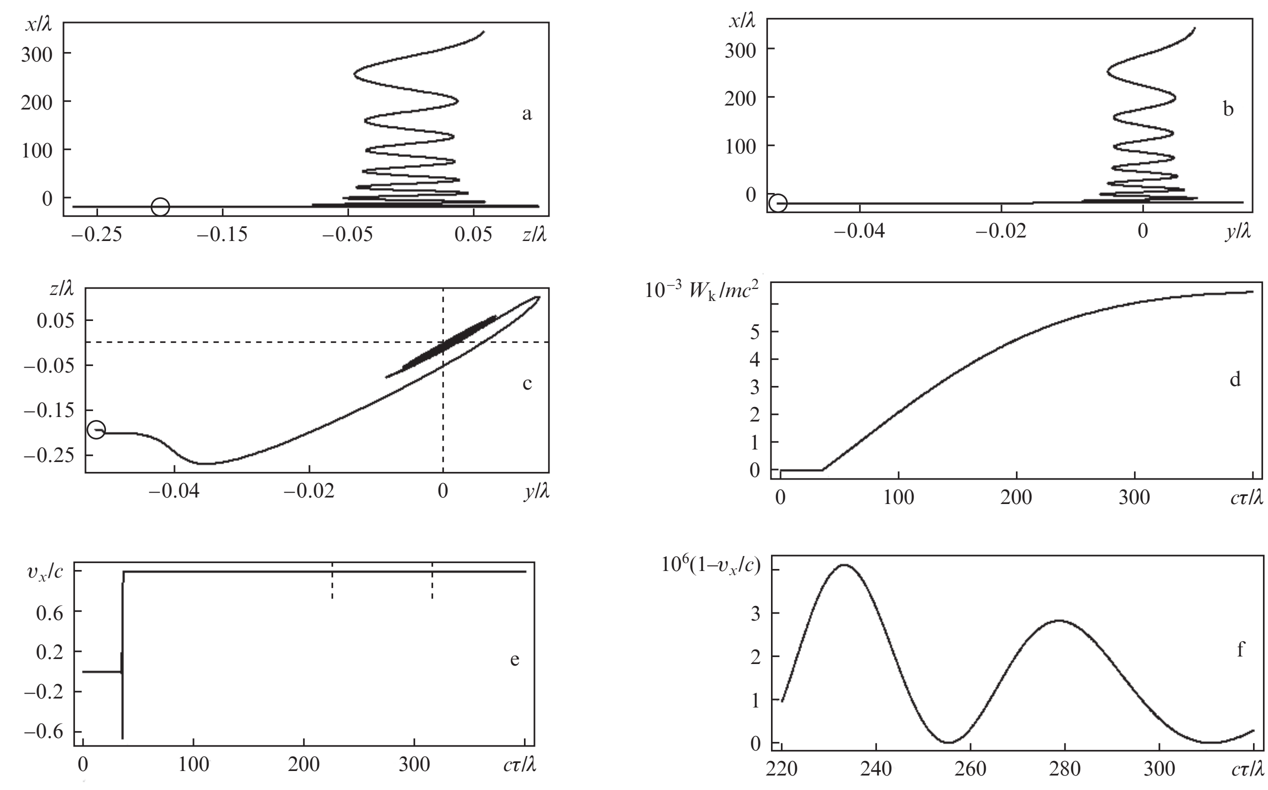


**Figure 2.** 2D trajectories of the electron motion in dimensionless coordinates ($x/\lambda$, $z/\lambda$) (a), ($x/\lambda$, $y/\lambda$) (b), ($z/\lambda$, $y/\lambda$) (c), and time dependences of the kinetic energy $W_k/mc^2$ (d) and the velocity component $v_x/c$ (e and f) for $\beta = 45°$. The parameters of the pulses are $s = 2$, $c\tau/\lambda = 3.3$, $\rho_{0\parallel}/\lambda = 200$, $\rho_{0\perp}/\lambda = 2.0$, $I_m/I_{rel} = 1000$. The coordinates of the initial position of the electron: $x_0/\lambda = -20$, $y_0/\lambda = -0.05$, $z_0/\lambda = -0.19$.

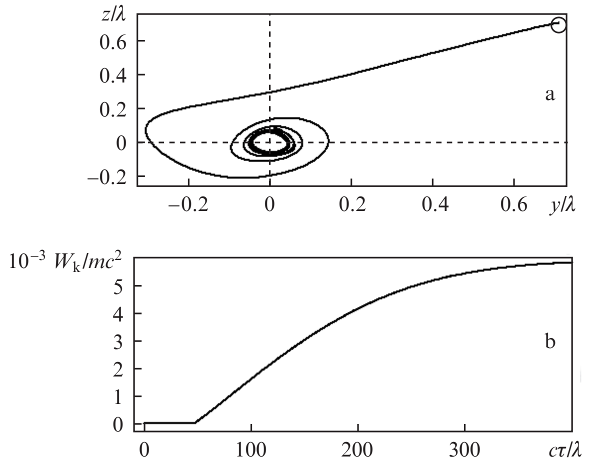


**Figure 3.** 2D trajectory of the electron motion in dimensionless coordinates ($z/\lambda$, $y/\lambda$) (a) and time dependence of the kinetic energy $W_k/mc^2$ (b) for $\beta = 45°$. The parameters of the pulses: $s = 2$, $c\tau/\lambda = 3.3$, $\rho_{0||}/\lambda = 200$, $\rho_{0\perp}/\lambda = 2.0$, $I_m/I_{rel} = 1000$. The coordinates of the initial electron position: $x_0/\lambda = -10$, $y_0/\lambda = 0.7$, $z_0/\lambda = 0.7$.

the plane ($y$, $z$) is somehow different from the case, considered above. The trajectories of electrons in the planes ($x$, $z$) and ($x$, $y$) are similar to those, presented in Figs 2a, b. The kinetic energy, accumulated by the electron, equals $W_k/mc^2 = 5800$ (2.9 GeV).

When the initial displacement of the electron along any of the axes is varied within the limits $|y_0/\lambda| \leqslant 1$, $|z_0/\lambda| \leqslant 1$, the general picture does not change. At the second stage of the motion the electron moves along the $x$ axis, symmetrically oscillating with respect to it, the amplitude of oscillation being slightly dependent on the value of the displacement. It is worth noting that when the initial displacement of the electron along the spatial coordinates is changed, the electron, captured by the laser field at the second stage moves in a single lattice cell, in which the strength of the field is negative.

From the performed calculations one can conclude that the dynamics of virtually all the electrons in the zone of interaction with the electromagnetic field of the standing wave, produced by three relativistic-intensity laser pulses with tilted amplitude fronts, consists of two stages considered above.

The general pictures of electron motion in the standing wave fields, formed by three and four Gaussian beams, differ insignificantly. Note that the kinetic energy, accumulated by the electron, the trajectory of its motion, the amplitudes of oscillations along the axes $z$ and $y$, and other dynamic parameters of electron motion in the field of a standing wave, formed by several laser pulses with plane wave fronts, demonstrate no essential difference from the cases considered above.

At the second stage of the motion the amplitude of the electron oscillations along the axes $z$ and $y$ increases with increasing pulse duration, and the electron can skip into the adjacent cells of the lattice. The kinetic energy accumulated by the electrons decreases. With the growth of the intensity of the laser beams the amplitude of oscillations decreases and the electron can again move in a single lattice cell.

In the cases $s = 1$ and $s = 2$ the effective acceleration of the electrons in the standing wave is possible only within a small interval of the angles $\beta$ near 45°. When the angle $\beta$ deviates from 45° the velocity of the region of the beams intersection along the $x$ axis differs from the speed of light $c$. Thus, for $\beta =$ 45.2° the kinetic energy of the electron decreases by an order of magnitude.

In the particular case, when the amplitude and the wave fronts of the laser pulse coincide ($\beta = 0°$), the electron in the field of the standing wave at the first stage of the motion oscillates along the axis $x$. At the second stage the electron is captured by one of the laser pulses and is expelled from the area of the standing wave formation.

As shown above, the dynamics of an individual electron in the field of a standing wave, formed by a group of laser pulses with relativistic intensity and inclined amplitude fronts, weakly depends on the initial position of the electron. Therefore, under the optimal conditions the appropriate calculations may be used to describe the dynamics of an ensemble of electrons. Such an ensemble arises, e.g., in the process of ionisation of a low-density gas by the leading edge of the laser pulse. Note that at the considered parameters of the laser pulses in the schemes for electron acceleration the impact of the laser field on the electrons is much greater than that produced by the force of Coulomb interaction between the electrons. The calculations were carried out without taking the interaction between the electrons of the ensemble into account; the action of the magnetic field of the electrons, accelerated in the field of the standing wave, is also neglected. These effects are planned to be taken into account in further publications.

The electrons of the ensemble, whose motion starts at the distances within a few wavelengths from the $x$ axis, under the direct interaction with the field of laser radiation are shifted towards this axis and, depending on the parameters of the laser radiation, are captured by one of the traps moving along the $x$ axis, which arise due to the interference of laser pulses. The strength of the electric field in such a trap is negative. The electromagnetic field in the trap acts on all captured electrons both along the $x$ axis and perpendicular to it. Under the action of the electric component of the field the electrons are accelerated along the $x$ axis up to the velocity, close to the speed of light $c$. As a result of the interference of laser pulses in the region, very close to the $x$ axis, the strength of the magnetic field is minimal, and directly on the $x$ axis it is zero. In the direction, perpendicular the $x$ axis, the strength of the magnetic field quickly increases.

In the scheme with four laser pulses, forming a standing wave, the angle between the vectors of the electric field strength of the adjacent pulses amounts to 90°. When the number of the interfering laser pulses is increased, provided that the wave vectors lie in a single plane, the distribution of the magnetic field in the standing wave in the plane, perpendicular to the $x$ axis, becomes close to the radially symmetric one (with respect to the modulus of the magnetic field strength). The electrons get into the trap with small velocity, directed perpendicular to the $x$ axis, with respect to which the electrons oscillate. The magnetic field returns back the electrons that decline from the $x$ axis and keeps them within the trap at the distance of $\sim 10^{-2}\lambda$ from the $x$ axis.

During the interaction with the field of the standing wave the compression of the electron ensemble along all the directions occurs, the transverse size of the electron bunch being reduced to $\sim 10^{-2}\lambda$ for $s = 1$ and $s = 2$. The trap moving with the speed of light $c$ along the $x$ axis successively captures electrons having different initial positions on the $x$ axis along the entire trajectory of its motion. The energy of electrons, captured by the trap, can achieve large values. The produced electron bunch moves along the $x$ axis together with its trap;

in this process the electrons also move with respect to the trap. This motion practically stops when the velocity of the electrons becomes close to the speed of light $c$. All electrons captured in the trap are concentrated in a very small volume, the size of which along the $x$ axis amounts to $\sim 10^{-3}\lambda$. The exact position of the electron concentration volume in the trap depends on the parameters of laser radiation.

The electrons are collected into a bunch with the volume $10^{-7}\lambda^3$ from the volume having the transverse dimension $\sim\lambda$ and the length $\sim 100\lambda$ (which is the entire length of the trajectory of the trap motion along the $x$ axis). As a result the density of electrons in the bunch may exceed the initial density of electrons in the ionised gas by $\sim 10^9$ times. For such length all electrons that form the bunch continuously interact with the standing wave. As a result of acceleration the kinetic energy of each electron in the bunch attains a few GeV. The produced electron bunch is symmetric with respect to the central axis of the standing wave.

In the proposed scheme the electrons are accelerated to the energy of a few GeV directly by the field of laser radiation. For the considered parameters of the laser pulses the strength of this filed attains 23 TV $m^{-1}$, which is nearly 200 times greater than the strength of the fields, produced in the experiments on laser-plasma acceleration of electrons [11, 12]. Correspondingly, the length, required for accelerating electrons to the same energy, in the proposed scheme appears to be much smaller. Another great advantage of the considered scheme is the formation of electron bunches with very small longitudinal and transverse dimensions.

It should be noted that by controlling the angles between the phase and amplitude fronts of the pulse one can always attain the velocity of the trap motion, slightly smaller than the speed of light by the value, optimal for electron acceleration. If the fronts possess some difference from the plane ones, the velocity of the trap motion can slightly change at some parts of the trajectory, and the angle of the front intersection may deviate from the optimal value. This may lead to a definite degradation of the electron acceleration parameters. Therefore, in the process of the interference field formation for electron acceleration following the proposed scheme it is of key importance to provide the necessary quality of fronts and the required values of the angles between the phase and amplitude fronts. If the parameters decline from the optimal ones, the final energies of the electrons will be lower than predicted, however, the acceleration will still take place. Detailed analysis of this issue is beyond the scope of the present paper and will be carried out elsewhere.

## 4. Conclusions

A new concept is proposed for direct acceleration of electrons by the optical field with special configuration, which arises due to the interference of several laser pulses, converging into a point and having the amplitude and phase fronts, propagating at a certain angle with respect to each other. In the case when this angle equals 45° the field traps in the frameworks of the considered configuration move in space with the speed of light. If the focal spots of the laser beams are asymmetric and their size is essentially greater than the wavelength in the direction of polarisation and nearly equal to the wavelength in the perpendicular direction, then the traps move over distances, comparable with the size of the focal spot in the direction of polarisation. The distribution of the filed in the traps simultaneously promotes the acceleration of electrons and the compression of the resulting electron beam. According to the calculation, for the experimentally implementable parameters of the laser pulses the longitudinal and transverse dimensions of the accelerated electron beam appear to be smaller than the wavelength by three and two orders of magnitude, respectively, while the electrons acquire the energy of a few GeV. The implementation of the proposed concept of laser acceleration of electrons will allow solution of a number of important fundamental and applied problems.

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