FEATURES OF THE MOTION OF CHARGED PARTICLES IN THE FIELD OF THE HIGH-FREQUENCY IMPULSE OF LARGE INTENSITY

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The results of analytical and numerical examinations of features dynamic of charged particles in a field of intensive electromagnetic waves are reported. It is shown that the trajectories of particles, which has initially different phases concerning of the homogeneous wave, essentially discriminate. As a result, the accelerated bunch breaks down. Trajectories of particles in a field of an electromagnetic impulse differ from each other a little. This feature allows using impulses for effective acceleration of clots of charged particles.
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1. INTRODUCTION

The motion of charged particles in a field of intensive electromagnetic waves has a series of the important features. These features allow to offer a series of new schemes of charged particles acceleration and generating of a short-wave radiation. It is important, that acceleration and a generating can be carried out in vacuum. The parameter of a wave force $\varepsilon = eE/mc\omega$ (parameter of nonlinearity) will use for quantitative measure of intensity. The conventional labels here are used. In the present report features of a motion of particles are investigated depending on a spatial arrangement of particles. It is shown that in a field of the homogeneous wave trajectories of particles strongly differ. It is shown that the electromagnetic impulse can be used for effective acceleration of particles in vacuum.

2. THE STATEMENT OF PROBLEM AND THE BASIC EQUATIONS

The components of electrical and magnetic fields of an electromagnetic impulse can be presented as

$$\mathbf{E} = \mathrm{Re}\left(-\frac{1}{c}\frac{\partial \mathbf{A}_0}{\partial t}\right), \mathbf{H} = \mathrm{Re}\left(\frac{1}{k_0}[\mathbf{kE}]\right), \qquad (1)$$

where $\psi \equiv \omega t - \mathrm{kr}$, $\mathbf{A}_0 = \alpha A_0(\psi)$; $\alpha = \{\alpha_x, i\alpha_y, \alpha_z\}$ - a vector of polarization of a wave; $k_0 = \omega / c$; ω, k - frequency of filling and a wave vector of an impulse. We shall use the following the dimensionless variable:
$\mathbf{p}_1 = \mathbf{p}/mc$, $\mathbf{k}_1 = \mathbf{k}/k_0$, $\tau = \omega\, t$, $\mathbf{r}_1 = k_0\mathbf{r}$,
$\mathbf{A} = e\mathbf{A}_0 / mc\omega$, $\mathbf{v}_1 = \mathbf{v}/c$.
In these variable the equation of motion gains a view (the coefficient "1" is fall down)

$$\dot{\mathbf{p}} \equiv \frac{d\mathbf{p}}{d\tau} = \mathrm{Re}\left[-(1-\mathbf{kv})\frac{\partial \mathbf{A}}{\partial \tau} - \mathbf{k}\left(\mathbf{v}\frac{\partial \mathbf{A}}{\partial \tau}\right)\right]. \qquad (2)$$

The equation (2) have known integrals:

$$\mathbf{p} - \mathbf{k}\gamma + \mathrm{Re}(i\mathbf{A}) = \mathbf{p}_0 - \mathbf{k}\gamma_0 + \mathrm{Re}(i\mathbf{A}) = \mathrm{const} = \mathbf{C}, \qquad (3)$$

where $\gamma = \sqrt{1+p^2}$ – the dimensionless energy of a particle (measured in units mc^2).

The equation (2) with taking into account integral (3) completely integrable in a laboratory frame. The solution looks like

$$\vec{p}_\perp - \vec{p}_{\perp 0} = \left(\vec{A} - \vec{A}_0\right), \quad p_\parallel - p_{\parallel 0} = \frac{\vec{p}_\perp^{\,2} + \vec{p}_{\perp 0}^{\,2}}{2\gamma\dot{\psi}}. \qquad (4)$$

Let's consider that the wave is propagating along an axis z, i.e. $\mathbf{k} = \{0, 0, k\}$.

3. DYNAMIC OF PARTICLES IN THE FIELD OF THE PLANE-POLARIZED WAVE

At examination dynamic of a particle in a field of a plane-polarized homogeneous plane wave ($\mathbf{A} = \mathbf{A}_0 e^{i\psi}$, $\mathbf{A}_0$=const) it has been shown, that their dynamic essentially depends from initial disposition of particles concerning a phase of a wave. So, if particles originally rested and were in phases πn they only entrain by the wave in a longitudinal direction. In a transverse direction they oscillate. The mean transverse momentum of them is equal to null. Such particles are displaced only in a longitudinal direction. The particles, which were in other phases, gain unequal to null mean transverse momentum. Quantity of this medial impulse and its direction depend from initial phases of particles concerning a wave. This particles scatter in different directions. Presence such scattering destroys structure of a bunch. Therefore, such scheme of charged particles acceleration is ineffective. In Figures 1 and 2 results of calculations of impulses and displacement of particles presented accordingly at a various initial arrangement concerning a phase of a wave (π, π/4, π/2, 3π/4, π).

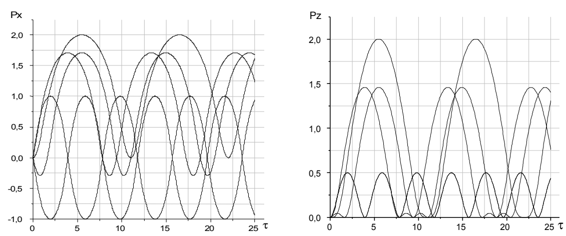

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Fig. 1. Impulses of particles at $\mathbf{A_0} = 1$ a) cross, b) a longitudinal impulse

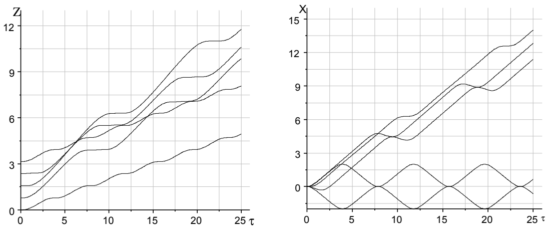

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Fig. 2. Entrainment of particles at $\mathbf{A_0} = 1$
a) longitudinal, b) a transverse direction

The scattering is considerably smaller for particles that initially have large longitudinal impulse. Such particles equally entrain in a longitudinal direction without dependence from their initially arrangement on phases of a wave. But in transverse direction this particles still scattered, however in much smaller degree. Results of calculations of particles displacement as function their initial standing concerning a phase of a wave (π, π/4, π/2, 3π/4, π) and their initial longitudinal impulse are presented in Figure 3.

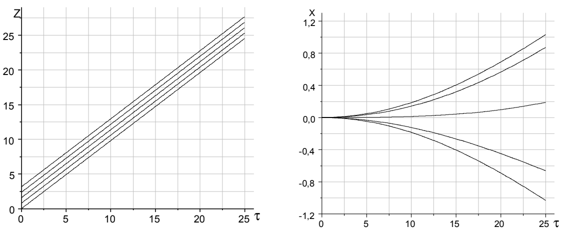

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Fig.3. Entrainment of particles at $P_{z0} = 5$ and $\mathbf{A_0} = 1$ a) longitudinal, b) a transverse direction

4. DYNAMIC OF PARTICLES IN THE FIELD OF THE WAVE WITH CIRCULAR POLARIZATION

In a field of a wave with circular (elliptic) polarization the basic features of a motion of particles are similar to features of motions in a field with the linear polarization.

Main distinctive feature dynamic of particles in a field of a wave with circular polarization is immunity of a longitudinal impulse of a particle from its initial phase. In Figure 4 it is visible, that quantities of longitudinal impulses of all particles completely coincide.

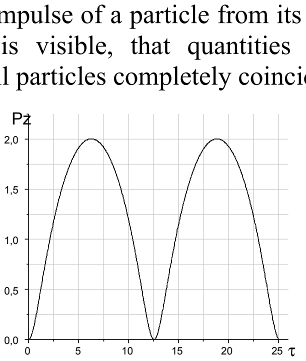

Fig. 4. Longitudinal impulse of particles

From the equations (4) it is possible to receive expression motions of particles featuring these important feature.

$$P_z = 2\mathbf{E}\,\left[1-\cos(\psi-\psi_0)\right] \qquad (5)$$

From this expression it is visible, that quantity of a longitudinal impulse is equal to all particles and does not depend on a initial arrangement of particles on phases. Really, because initial value of Ψ is ψ_0, the P_z for all particles coincide. The trajectories of particles in impulse space have form of spirals (look Fig. 5).

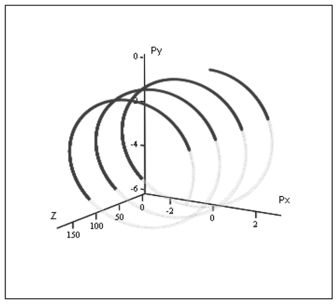

Fig. 5. Trajectory of particles in space of impulses

5. DYNAMIC OF PARTICLES IN THE FIELD OF THE HIGH-FREQUENCY IMPULSE

It has been investigated dynamic of particles in a field of an impulse $\mathbf{A} = \mathbf{A_0}\exp\left[-\beta\left(\psi-\psi_0\right)^2 + i\psi\right]$. Main feature dynamic is that fact that this of dynamic practically does not depend on a initial arrangement of particles in space. Their trajectories are similar. All of them entrain in a longitudinal direction and oscillate in cross, and this entrainment happens on a spiral trajectory (look Fig. 7). Interesting significant feature of a motion of particles in a field of the high-frequency impulse having circular polarization, is that fact that the longitudinal impulse reproduces the shape enveloping an impulse. Such features of dynamic of particles in an impulse allow using it for effective acceleration of charged particles.

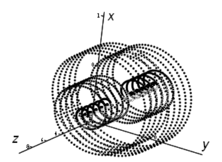

Fig.6. Trajectories of particles

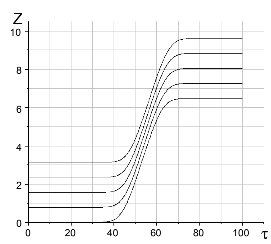

Fig.7. Entrainment of particles in longitudinal direction

Time dependence of an impulse and the coordinates of a particle found at the numerical solution of the equation (2) for case of circular polarization of a field of an impulse are represented in Fig.8. The solution is obtained for particles, which initially were in rest at $A_0 = 1$, $\beta = 0.01$, $\psi_0 = 50$.

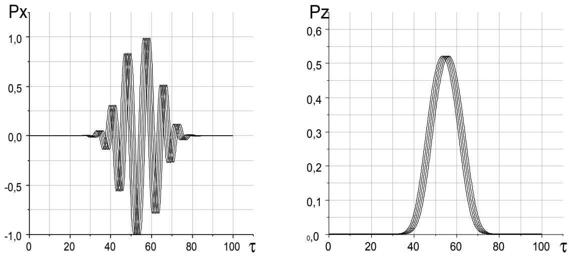

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Fig.8. Impulses of particles a) cross, b) a longitudinal impulse

As an example of high efficiency of charged particles acceleration we shall consider bunch, which have initially energy $\gamma_0 = 10$. Let on such clot acts the impulse with amplitude $\mathbf{A_0} = 3$. In this case it is useful to investigate two different cases.

In the first case we shall consider, that initially the impulse is far enough from charged particles. In this case the field strength of the impulse in the place where are bunch is slowly builds up. This case corresponds to a large value ψ_0. In particular, at $\psi_0 = 50$ dependence of a longitudinal impulse on time it presented in Figure 9a. From this figure it is visible, that all particles have practically equal trajectories. In a transverse direction the particles do not scattered. Such laser impulse is very convenient for using for acceleration. Thus, as a result of interaction of particles with a field of such impulse, particles were accelerated to energies $\gamma \approx 100$, and acceleration happens at a distance that equal 0.4 cm.

In the second case - the beginning of interaction corresponds to the peak value of pulse amplitude. It means, that quantity ψ_0 is equal to null. Dependence of a longitudinal impulse on time for this case presented in Figure 9b. As a result of interaction of particles with a field of such impulse they were accelerated to large energies ($\gamma \approx 350$). This acceleration happens at a distance ~ 0.8cm.. To a regret, in this case there are some particles that are scattered in a transverse direction. So at $\lambda \approx 10^{-4}$ the cross size of bunch will have transversal size $\Delta x \approx 3 \cdot 10^{-3} cm$. It is necessary to note, that maximal quantity of a longitudinal impulse in this case can be estimated by formula: $\gamma_{\max} \approx \gamma_0 \left(1 + 4 \cdot A^2\right)$, which coincides with the formula obtained in [2] for a case of a homogeneous field.

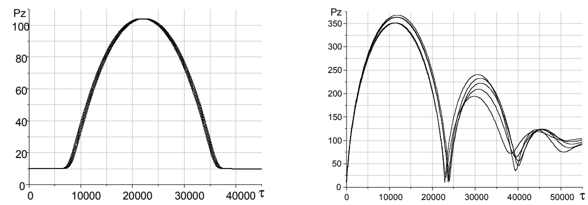

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Fig. 9. Dependence of a longitudinal impulse on time a) $\psi_0 = 50$. b) $\psi_0 = 0$

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ОСОБЕННОСТИ ДВИЖЕНИЯ ЗАРЯЖЕННЫХ ЧАСТИЦ В ПОЛЕ ВЫСОКОЧАСТОТНОГО ИМПУЛЬСА БОЛЬШОЙ НАПРЯЖЕННОСТИ

В.А. Буц, В.В. Кузьмин

Изложены результаты аналитического и численного исследований особенностей динамики заряженных частиц в поле интенсивных электромагнитных волн. Показано, что в поле однородной волны траектории частиц, находящихся в разных фазах волны, существенно различаются. Ускоряемый сгусток при этом разваливается. Траектории частиц в поле электромагнитного импульса мало отличаются друг от друга. Эта особенность позволяет использовать импульсы для эффективного ускорения сгустков заряженных частиц.

ОСОБЛИВОСТІ РУХУ ЗАРЯДЖЕНИХ ЧАСТОК У ПОЛІ ВИСОКОЧАСТОТНОГО ІМПУЛЬСУ ВЕЛИКОЇ НАПРУЖЕНОСТІ

В.О. Буц, В.В. Кузьмін

Викладено результати аналітичного та чисельного досліджень особливостей динаміки заряджених часток у полі інтенсивних електромагнітних хвиль. Показано, що в полі однорідної хвилі траєкторії часток, що знаходяться в різних фазах хвилі, істотно розрізняються. Згусток, що прискорюється, при цьому розвалюється. Траєкторії часток у полі електромагнітного імпульсу мало відрізняються один від одного. Ця особливість дозволяє використовувати імпульси для ефективного прискорення згустків заряджених часток.