DYNAMICS OF THE CHARGED PARTICLES IN A FIELD OF INTENSIVE ELECTROMAGNETIC WAVES

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The results of the investigations of the charged particles dynamics in field of intense electromagnetic waves and electromagnetic impulse are represented. It was shown, that the traditional scheme of the acceleration, such as inverse free electron laser in such fields are not efficiently. Accelerating particles by laser impulse allows to all accelerated particles to have absolutely identically trajectories. The limitation on maximum energy, which particles can received and which is caused by radiation friction are removed.

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1. INTRODUCTION

The acceleration of the charged particles by a field of laser radiation in vacuum represents tempting prospect [1,2]. One of the most interesting and perspective scheme of acceleration is the scheme of the inverted free electron laser (IFEL). However, as we shall see below, with increase of intensity of laser radiation in the scheme IFEL the stochastic instability develops. This scheme ceases to be effective. We shall show that the acceleration charged particles by laser pulse can be enough effective. At laser acceleration the particles are moving with acceleration. They radiate. This radiation can restrict maximal energy, which particles can receive at laser acceleration [3]. Below we shall show that this restriction can be deleted. Except it we shall show that forces of friction can promote laser acceleration.

2. THE SCHEMENS OF THE INVERSE FREE ELECTRON LASER

Acceleration in scheme IFEL occurs by field of a combinational electromagnetic wave which is formed as a result of beat of two laser waves. Accelerated particles are in Cherenkov resonance with this beat-wave. The dimensionless amplitude of a beat-wave is proportional to product of amplitudes of the waves forming this wave. In existing schemes it is supposed, that amplitudes of laser waves in scheme IFEL are small. The amplitude of a beat-wave is smaller. Therefore there is a natural desire to increase these amplitudes. However, as we shall see below, such increase leads to development of stochastic instability. Presence of this instability does scheme IFEL practically disabled. Below we shall define values of amplitudes of laser fields which else are admissible in scheme IFEL.

Let's consider dynamics of the charged particles in a field of several electromagnetic waves. Expressions for electric and magnetic fields of these waves can be presented in such kind:

$$E = \sum_n E_n \,,\; H = \sum_n H_n \,,$$

$$E_n = \mathrm{Re}(\breve{a}_n \cdot e^{i\psi_n}) \,, \vec{H}_n = \frac{c}{\omega_n}[\vec{k}_n \vec{E}_n] \,, \qquad (1)$$

where $\psi_n = \breve{k}_n r - \omega_n t$, $\breve{a}_n \equiv eE_n / mc\omega_0$.

The equations of movement in fields (1) look like:

$$\frac{dP}{dt} = e\vec{E} + \frac{e}{c}[\vec{v}\vec{H}] \,. \qquad (2)$$

These equations are convenient rewrite in dimensionless variables:

$$P \to \frac{P}{mc} \,,\; \omega_n = \frac{\omega_n}{\omega_0} \,,\; \dot{\vec{P}} \equiv \frac{dP}{d\tau} \,,\; \tau \equiv \omega_0 t \,,\; \vec{\beta} = \frac{\bar{v}}{c} \,,$$

$$\vec{E}_n \equiv \frac{eE_n}{mc\omega} \,,\; \vec{k}_n \equiv \frac{k_n c}{\omega} \,,\; \vec{r} \equiv \frac{\omega_0}{c}\vec{r} \,.$$

$$\dot{\vec{P}} = \sum_n E_n\left(\omega_n - \breve{k}_n \vec{\beta}\right) + \sum_n \breve{k}_n\left(\vec{\beta}E_n\right) \qquad (3)$$

$$\dot{\gamma} = \frac{P}{\gamma}\sum_n \omega_n \vec{E}_n \,,$$

where: $E_n = \mathrm{Re}\left(\breve{a}_n \cdot e^{i\psi_n}\right)$ $\psi_n \equiv k_n \breve{r} - \omega_n \tau$.

For the further analysis it is convenient to introduce the auxiliary characteristic of a particle, which we in the further shall name partial energy of a particle. This energy satisfies to the following equation:

$$\dot{\gamma}_n = \omega_n(\vec{\beta}E_n) \,. \qquad (4)$$

The equations (3) (4) have following integral:

$$\vec{P} - \sum_n \mathrm{Re}(i \cdot \vec{a}_n \cdot e^{i\psi_n}) - \sum_n \frac{k_n}{\omega_n}\gamma_n = \vec{C} \,. \qquad (5)$$

Generally, the equations (3) and (4), together with integral (5), can be studied only by numerical methods. For receiving of analytical results we shall consider, that the parameter a each of waves acting on a particle is small. In this case all characteristics (its energy, an impulse, coordinate, velocity) can be presented in the form of the sum slowly varying and quickly varying component:

$$\breve{P} = \breve{\bar{P}} + \breve{\tilde{P}} \quad \gamma_n = \bar{\gamma}_n + \tilde{\gamma}_n \,.$$

In this case it is possible to receive following expressions and the equations which connect fast and slow variables:

$$\vec{\bar{P}} = \sum_n \frac{k_n}{\omega_n}\bar{\gamma}_n + C \,,$$

$$\breve{\tilde{P}} = \sum_n \mathrm{Re}(i \cdot \vec{a}_n \cdot e^{i\psi_n}) + \sum_n \breve{k}_n \tilde{\gamma}_n / \omega_n \qquad (6)$$

$$\dot{\tilde{\gamma}}_n = \omega_n \cdot \breve{\bar{v}} \cdot E_n = \omega_n \cdot \breve{\bar{v}} \cdot \mathrm{Re}(\breve{a}_n \cdot e^{i\psi_n}) \,,$$

$$\dot{\bar{\gamma}}_n = \omega_n \cdot \breve{\tilde{v}} \cdot E_n \qquad \tilde{\gamma}_n = \mathrm{Re}(\Gamma_n e^{i\psi_n}) \,,$$

where $\Gamma_n = -i\omega_n \bar{v} \cdot \breve{a}_n / \dot{\psi}_n$.

The equations for fast variables can be integrated. The equations for slow variables will get a following form:

$$\dot{P} = \sum_{m,n} \mathring{k}_n \frac{1}{\gamma}\left[\mathrm{Re}\left(i\cdot \mathring{a}_m \cdot e^{i\psi_m}\right)\right]\left[\mathrm{Re}\left(\mathring{a}_n \cdot e^{i\psi_n}\right)\right],$$

$$\dot{\gamma} = \frac{1}{\gamma}\sum_{m,n} \mathrm{Re}(i\cdot \mathring{a}_m \cdot e^{i\psi_m})\omega_n \,\mathrm{Re}(\mathring{a}_n \cdot e^{i\psi_n}) =$$

$$= \sum_{m,n} \frac{1}{2\gamma}\omega_n \cdot \mathring{a}_n \cdot \mathring{a}_m [\cos(\psi_m + \psi_n + \pi/2) + \cos(\psi_m - \psi_n + \pi/2)] \qquad (7)$$

The equations (7) are equivalent to the equation of a nonlinear pendulum (a mathematical pendulum) on which external periodic force acts. Really, let's consider example, when there are available only two waves. Then if we introduce new variable $\theta \equiv \psi_1 - \psi_2$, the equations (7) can be rewritten in the form:

$$\frac{d\gamma}{d\tau} = \frac{1}{\gamma} a \cdot \Omega\cos\theta + F(\tau), \frac{d\theta}{dt} = \mathring{\chi}\mathring{v} - \Omega = \Delta(\gamma), \qquad (8)$$

where: $\breve{\chi} \equiv k_1 - k_2$, $\Omega \equiv \omega_1 - \omega_2$, $a = a_1 \cdot a_2$, $F(\tau)$ - periodic function.

We supposed that $\Omega / \chi \cong v$.

At small changes of energy, the system (8) can be rewrite in the form:

$$\ddot{\theta} = \left(\frac{\partial \Delta}{\partial \gamma}\right)_{\gamma_0} \frac{a \cdot \Omega}{\gamma_0}\cos\theta + F(\tau). \qquad (9)$$

We fulfilled series of numerical researches of the equations (3). The dynamics of particles in the most interesting configuration of fields which is represented with a field of two electromagnetic waves, which are moving towards each other, was investigated. Such configuration meets in the schemes of acceleration IFEL. The basic results of these numerical researches consist in the following:

– If amplitudes of waves are small (a_1 and a_2 less than 0.1) qualitatively dynamics of particles are similar to dynamics of a mathematical pendulum.

– When amplitudes of waves become greater 0.1, the dynamics of some particles, namely those particles which are located in a vicinity separatrix of mathematical pendulum, becomes chaotic. And the more the amplitude of waves, the more of particles joins to chaotic dynamics.

– Only those particles, which appear in zero phases of a beat-wave, do not participate in chaotic dynamics. They are located in islands of stability. However with increase amplitude of the waves the number of such particles becomes less.

For an illustration of formulated above results on Fig.1 characteristic dependence of a longitudinal impulse of a particle from time is presented. From this figure irregular dynamics of movement of a particle is visible. The same irregularity is proved by the statistical analysis: spectra of movement is wide (Fig. 2), correlation function quickly falls down, Lyapunov's parameters are positive.

The received numerical results are in the good qualitative consent with the analysis of dynamics of particles on the basis of the equation (9).

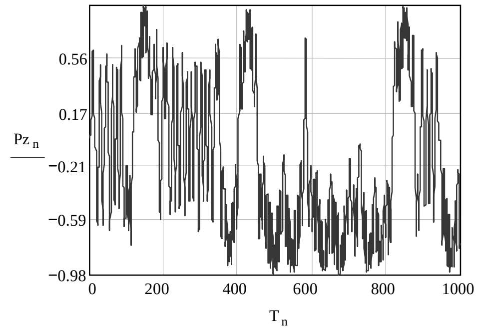

Fig. 1. Dependence of a longitudinal impulse of a particle on time

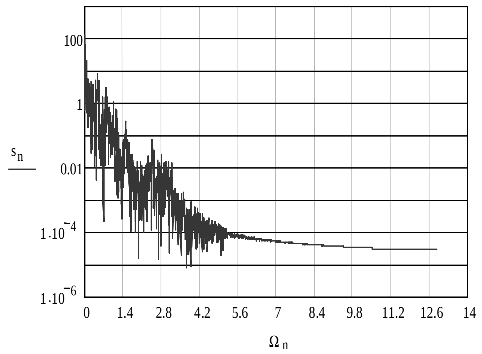

Fig. 2. A spectrum of movement of a particle at $a = 0.5$

3. INTERACTION OF A PARTICLE WITH AN IMPULSE OF AN ELECTROMAGNETIC WAVE

One of interesting schemes of acceleration is the scheme in which movement of the charged particle occurs in a field of an impulse of the flat running electromagnetic wave. This impulse characterized by vector potential. $\bar{A} = \bar{A}\left(\tau - \bar{k}\cdot \mathring{r}\right) \equiv \bar{A}(\psi)$. Such scheme was considered. In this case it is possible to receive analytical expressions, describing dynamics of the charged particles [4].

In case of interaction of particles with an impulse of a running electromagnetic wave, the particles are dragging by the wave along wave-vector. Under it's, the longitudinal impulse oscillate, but don't change his sign. The longitudinal coordinate is defined by integral from non-negative function. Character of interaction of particles with a wave does not depend on their initial position since front of an impulse consistently run over on all particles and they appear in identical entry conditions concerning a phase of a wave. And in a field of a high-frequency impulse having circular polarization, a longitudinal impulse of particles repeats the form of the impulse envelope.

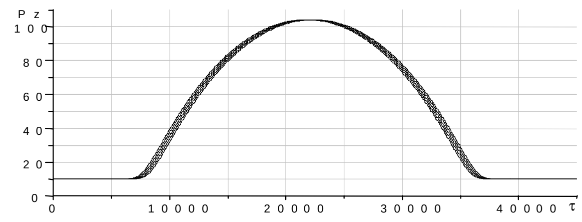

Fig. 3. Dependence of a longitudinal impulse on time ($\psi_0 = 50$)

As an example of an opportunity of acceleration of a bunch of the charged particles we shall consider a bunch which has initial energy $\gamma_0 = 10$. Let on such bunch the transversal electromagnetic field with components defined by expression:

$\partial A_x / \partial\psi = A_0 \exp[-\beta(\psi - \psi_0)^2] \cdot \cos\psi$ acts. ($A_0 = 3$, $\beta = 0.01$). In Fig. 3 it is visible, that on distance 0.4cm. energy of particles reaches value $\gamma \approx 100$. Besides, all particles have practically identical trajectories. Such laser pulse is convenient for acceleration.

4. ROLE OF FORCES OF FRICTION AT LASER ACCELERATION

The authors of work [3], considering acceleration of electrons by laser radiation, have equated force of radiating friction to accelerating forces (forces of high-frequency pressure). As a result they have found that in a field of laser radiation the electrons cannot get energy greater, than 200 MeV ($\lambda \sim 1\mu k$).

In the present section we shall show, that forces of friction, including forces of radiating friction, can promote transfers of energy from an external laser field to accelerated particles. Besides restriction on the maximal size of energy in 200 MeV in common case can be deleted (see [5] too).

For the description of a role of friction we use equations (3) in which we should to add force of friction into right part. In the beginning we shall consider model in which we shall not concretize the nature of these forces:

$$\frac{dp}{d\tau} = \mathrm{Re}\left\{\left((1-\mathring{k}\mathring{v}) \cdot \mathring{a} + \mathring{k}(\mathring{v} \cdot \mathring{a})\right)\exp(i\Psi) - \mu\mathring{v}\right\}. \quad (10)$$

From (10) it is possible to receive a following equation:

$$\frac{d}{dt}\{\mathring{p} - k\gamma + \mathrm{Re}(i \cdot \mathring{a} \cdot \exp(i\Psi))\} = -\mu\left[\mathring{v} - kv^2\right]. \quad (11)$$

If friction is absent $(\mu = 0)$, expression in braces represents integral of the equation (10). We shall consider, that $\breve{a} = (a,0,0)$; $\breve{\alpha} = (1,0,0)$, $k = (0,0,1)$. In this case the equation (10) can be simplified essentially.

Let's make such replacement:

$$p_x = a \cdot \sin\Psi + \left(p_{x,0} - a \cdot \sin\Psi_0\right) + \rho_x ,$$
$$p_z = \left(p_x^2 / 2I\right) + \left(p_{z,0} - p_{x,0}^2 / 2I_0\right) + \rho_z . \quad (12)$$

Here ρ_x and ρ_z new dependent variables, and «0» are designated initial values of variables. From system (11) it is easy to find the following equations for definition ρ_x and ρ_z:

$$\rho_x{}' = -(\mu / I)[\rho_x + a \cdot \sin\Psi]$$
$$\rho_z{}' = -(\mu / I)\left[\rho_z + \left(p_x^2 / 2 \cdot \gamma \cdot I^2\right) - \left(p_x / I\right)\right]. \quad (13)$$

The analysis of these equations shows that if $\gamma \cdot I > 1$, then the appearing friction will lead to acceleration. If the opposite inequality takes place, then particles will be brake by friction. We will have the same results if friction forces are forces of radiating friction. It is important, that acceleration can be unlimited. Numerical researches completely confirm the received results.

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ДИНАМИКА ЗАРЯЖЕННЫХ ЧАСТИЦ В ПОЛЕ ИНТЕНСИВНЫХ ЭЛЕКТРОМАГНИТНЫХ ВОЛН

В.А. Буц, В.В. Кузьмин

Изложены результаты исследований динамики заряженных частиц в поле интенсивных электромагнитных волн и электромагнитных импульсов. Показано, что традиционная схема ускорения типа обращенного лазера на свободных электронах в таких полях мало эффективна. При ускорении заряженных частиц лазерным импульсом все ускоряемые частицы могут двигаться абсолютно идентично. Сняты ограничения на предельно возможные значения энергии ускоряемых частиц при лазерном ускорении, которые обусловлены радиационным трением

ДИНАМІКА ЗАРЯДЖЕНИХ ЧАСТОК У ПОЛІ ІНТЕНСИВНИХ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ

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Наведено результати досліджень динаміки заряджених часток у полі інтенсивних електромагнітних хвиль й електромагнітних імпульсів. Показано, що традиційна схема прискорення типу зверненого лазера на вільних електронах у таких полях мало ефективна. При прискоренні заряджених часток лазерним імпульсом всі прискорені частки, можуть рухатися абсолютно ідентично. Знято обмеження на гранично можливі значення енергії прискорених часток при лазерному прискоренні, які обумовлені радіаційним тертям.