PECULIARITIES OF PARTICLES AND FIELD DYNAMICS AT CRITICAL INTENSITY OF ELECTROMAGNETIC WAVES (PART I)

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Some results of study of the charged particles that are moving in a field of intensive electromagnetic waves are represented. The integrals are investigated and some schemes of laser acceleration are considered. It was revealed that the most effective scheme of acceleration is the scheme, in which the laser pulse with circular polarization is used. Is shown that the forces of radiating friction can promote transferring of energy from a laser field to particles. Besides is shown, that for laser acceleration the force of radiating friction are considerably less essential, than in cyclic accelerators.
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1. INTRODUCTION

We shall understand fields with critical intensity the fields, at which there are qualitatively change of interaction dynamics of particles and fields. In this section we shall consider dynamics of particles in intensive electromagnetic fields. The measure of intensity will be served a parameter of a wave force $\varepsilon = eE/mc\omega$. The condition $\varepsilon > 1$ means that $E > 10^5 V/cm$ for $\lambda = 10 cm$ and $E > 10^{10} V/cm$ for $\lambda = 10^{-4} cm$. In such fields the charged particles get velocity close to velocity of light during time about one period of a wave. The long synchronism is not necessity for an effective exchange of energy between particles and fields In these conditions. It means, that the resonant conditions of particles and fields interaction cease to play a significant role in interaction. The analytical solving of a task about movement of particles thus encounters significant difficulties, because there is no usual small parameter $\varepsilon << 1$. However in many cases it is possible to receive the significant information on dynamics of particles, using integrals of movement. Besides, in some enough simple cases, it is possible to receive the analytical solutions. Such cases are key for understanding of interaction of intensive fields with particles. Below we shall consider such opportunities.

2. FORMULATION OF A TASK

Let's consider the charged particle, which goes in an external constant magnetic field H_0 and in a field of an electromagnetic wave with any polarization. The vector $\vec H_0$ is directed along an axis z. Let wave have the following components

$$\vec e = \mathrm{Re}\,\vec E \exp\left(i\vec k\vec r - iwt\right);$$

$$\vec E^{\,o}\left\{E_0\left(\alpha_x, i\alpha_y, \alpha_z\right)\right\}$$

$$\vec H = \mathrm{Re}\frac{c}{w}\left[\vec k\vec E\right]\exp\left(i\vec k\vec r - iwt\right),$$

where $\vec\alpha^{\,o}\left\{\alpha_x, i\alpha_y, \alpha_z\right\}$ - vector of polarization.

If time measure in ω^{-1}, velocity in c, magnitude of a wave vector k in ω/c, a pulse in mc and to enter dimensionless amplitude of a field $\varepsilon_0 = eE_0/mc\omega$ than one can transform the equations of motion in a kind:

$$\dot{\vec P} = \left(1-\frac{\vec k\vec p}{\gamma}\right)\mathrm{Re}\left(\vec{\mathcal E}\cdot e^{i\Psi}\right)+\frac{\omega_H}{\gamma}[\vec p\vec e]+\frac{\vec k}{\gamma}\mathrm{Re}\left(\vec p\cdot\vec{\mathcal E}\right)e^{i\psi}; \quad (1)$$

where $\tau \equiv \omega t,\ \vec e \equiv \vec H/H_0;\ \omega_H \equiv eH_0/mc\omega;\ \psi = \vec k\vec r - \tau.$

From the equation (1), it is possible to find following integral of movement

$$\vec p - \mathrm{Re}\left(i\vec\varepsilon\cdot e^{i\psi}\right)+\omega_H\left[\vec r\vec e\right]-\vec k\gamma = const. \quad (2)$$

The movement of a particle can occur only on the following surface

$$\gamma^2 = p_\parallel^2 + p_\perp^2 + 1 \quad (3)$$

The surface (3) represents hyperboloid of rotation. The hyperboloid surface (3) is represented in a fig. 1 and 2.

The analysis of integrals. If ($k_x = k_y = 0,\ k_\perp = 0$), longitudinal component of integral assume the form:

$$p_\parallel - k_z = p_{\parallel,0} - k_z\gamma_0 \equiv C = const \quad (4)$$

In figure 1 the characteristic kind of hyperboloid section $\gamma^2 = 1 + p_\parallel^2 + p_\perp^2$ by planes of integrals (4) is represented at interaction of a particle with slow waves ($k_z > 1$). In figure 2 - for a case $k_z < 1$.

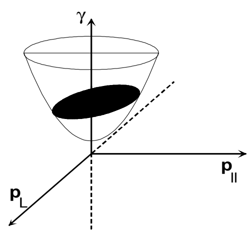

Fig. 1

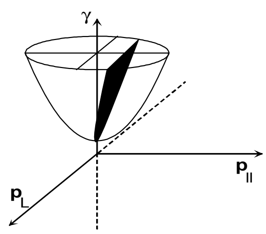

Fig.2

The important physical conclusions can be made from these two figures. In particular, it is visible, that at interaction of a particle with a fast wave ($k_z < 1$) the energy of a particle is not restricted by integrals and can reach any value. It is namely that case, at which it is potentially possible unlimited acceleration, and possible great transformation of energy from particles to the wave. Using integrals (2) it is possible also to find out many important features of movement of particles. In particular, it is possible to find conditions, at which the particles completely pass all their energy to a wave.

3. ACCELERATION OF THE CHARGED PARTICLES IN VACUUM

If the external magnetic field is absent, the equations of movement (1) can be solved [1]. Lets charged particles move in vacuum and are in a field of a flat electromagnetic wave of the large intensity. Such particles carry along a direction of this wave propagation. Let's note the most important features of such entrainment [1]. If the particle originally were in rest, average velocity of a particle in a direction of wave propagation is close to $v = c \cdot \varepsilon^2 / \left(4 + \varepsilon^2\right)$. As the result of this entrainment varies also period of a wave, which is "perceived" by a particle: $T = T_0 \cdot \left(1 + \varepsilon^2 / 4\right)$ The longitudinal pulse periodically varies, but the average size of this pulse is not equal to zero: $p_z = \varepsilon^2 \left(1 - \cos 2\psi\right) / 2,\ \psi = \tau - z$. If the particle had the large enough initial energy, than the dynamics can qualitatively change. So, the period of a wave concerning a particle becomes equal $T = T_0 \cdot \left(\gamma^2 + \gamma^2 \cdot \varepsilon^2 / 2\right)$. The increase of the period in this case is caused by two factors. The first factor is caused by usual effect Doppler. Second addend is caused by nonlinear dynamics of a particle in a field of an intensive electromagnetic wave. The maximal size of a longitudinal pulse in this case also essentially grows: $p_z = p_{z,0} + \varepsilon^2 \cdot \gamma / 2$ The energy changes in boundaries $\gamma_0 \leq \gamma \leq \gamma_0 \left(1 + 4\varepsilon^2\right)$. Such dynamics of particles allows to offer the various simple schemes of high-frequency acceleration of particles and new schemes of excitation of short-wave radiation (see, [1-3]). However at such schemes of acceleration the accelerated particles run away in a cross direction. For illustration of such scattering in figure 3 is represented dependence of a cross deviation of particles ($P_{z0} = 5$ and $\varepsilon = 1$) from their initial arrangement concerning a phase of a wave. The presence scattering makes this scheme of acceleration not very interesting. The situation essentially varies at acceleration of particles by a field of a high-frequency pulse $\vec{\varepsilon} = \vec{\varepsilon}_0 \exp\left[-\beta\left(\psi - \psi_0\right)^2 + i\psi\right]$ having circular polarization. In a field of such pulse all particles have coincide trajectories. It is interesting, that the longitudinal impulse of particles repeats the form of a pulse envelope. In figure 4 the dependence of a longitudinal impulse of particles on time is submitted.

Initially particles were in regular intervals located concerning a phase of a high-frequency wave. It is visible, that the trajectories of all particles completely coincide. Such feature of dynamics of particles in a pulse allows to use it for effective acceleration. Especially for acceleration of particles having the large initial velocity.

4. INFLUENCE OF FRICTION AT LASER ACCELERATION

At interaction electrons with intensive laser field there is a radiation arising. This radiation, as well as the radiation in cyclic accelerators, can limit energy, which particles can acquire. In work [3], examining acceleration of electrons by a field of laser radiation, the authors have equated force of radiating friction to accelerating forces (forces of high-frequency pressure). In result they have found, that in a field of laser radiation the electrons can not get energy large, than 200 MэВ ($\lambda \sim 1\mu k$). It is necessary to notice, that, as force of high-frequency pressure and force of radiating friction both are proportional ε^2, this result does not depend on intensity of a field of laser radiation. In this sense he is universal.

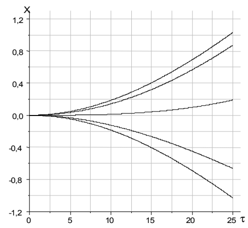

Fig.3

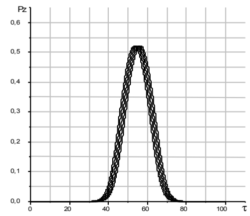

Fig.4

In the present section we shall show, that the forces of friction, including forces of radiating friction, can promote transfers of energy from an external laser field to accelerating particles. Besides will be shown that the restriction on the maximal size of energy in 200 MeV, which can get particles in a field of laser radiation, generally is absent. Let particle move in a field of a homogeneous flat electromagnetic wave, which is propagates in vacuum along an axis z and has only two components: E_x, H_y. The equation of the charged particle movement with taking into account the force of friction looks like:

$$\frac{d\vec{p}}{dt} = q\vec{E} + \frac{1}{c}\left[\vec{v} \cdot \vec{H}\right] + \vec{F}_f \quad . \qquad (5)$$

This equation differs from investigated in [1] only by presence of force of friction. If this force is absent, the variable $I \equiv \gamma - p_z = const$ is integral of the equation (5). If the force of friction is present, the size I already ceases to be integral. Let's consider that the force of friction can be presented as $\vec{F}_f = -\mu \vec{p} / \gamma$, here $\mu = const$. Then for definition I from (5) it is possible to receive the following equation:

$$\frac{dI}{d\tau} = -\mu \frac{I}{\gamma} + \frac{\mu}{\gamma^2} \quad . \qquad (6)$$

The general solution of the equation (6) is possible to write down as:

$$I = \exp(-) \cdot \int_0^{\tau} \frac{\mu}{\gamma^2} \cdot \exp(+) \cdot d\tau\,, \qquad (7)$$

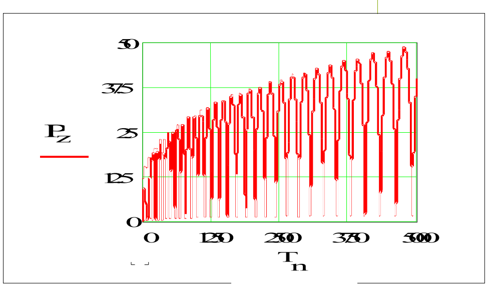

Fig.5

where $\exp(\pm) \equiv \exp(\pm\mu\int^{\tau} d\tau/\gamma)$. Thus, the size of integral I tend to size $1/\gamma$. The characteristic time in inverse proportion to parameter μ. From formula (5) is possible to estimate and maximal size of a longitudinal pulse, which the particle can achieve: $p_z \sim \varepsilon^2/\mu$. Let's consider now force of high-frequency friction.. We shall be limited to a case of relativistic movement ($\varepsilon \geq 1$). In our case we have only two components of an electromagnetic field (E_x, H_y). Taking into account, that $E_x = H_y$, and also, that the four-vector of velocity in our designations looks like $u^k = (\gamma, \vec{p})$, $u_n = (\gamma, -\vec{p})$, the force of radiating friction can be presented by the following expression.

$$\vec{F}_f = -\frac{\omega}{\Omega}\cdot\varepsilon^2\cdot I^2\cdot\frac{\vec{p}}{\gamma}\cdot\cos^2(\psi),$$

Where «frequency» $\Omega_e = 3mc^3/2e^2 = 1{,}8\cdot10^{23}$ сек$^{-1}$.

It is easy to see that in this case the size of integral is decreases, though not so fast as in the previous case. The point $I = 1/\gamma$ is a stable stationary point. In a fig. 5 the dependence of a longitudinal pulse on time is submitted at presence of force of friction ($\varepsilon = 5$, $\mu = 5\cdot10^{-3}$). In a fig. 6 the dependence of a longitudinal pulse on time is submitted at the following values of parameters: $\varepsilon = 5$, $\mu = 5\cdot10^{-3}$, $p_{z,0} = 20$. From this figure it is visible, that the energy of a particle already large than 200 MeV. Let's compare laser acceleration to acceleration in the cyclic accelerator. The expression for capacity of radiation in the accelerator can be presented as: $W = 2\cdot e^2c\cdot K^2\cdot\gamma^4/3$,

where K - curvature of an orbit. In case of laser acceleration K grows proportionally to square energy ($K \sim 1/\gamma^2$). Therefore capacity of radiation does not vary with growth of energy and problem connected to growth of radiating losses, does not arise.

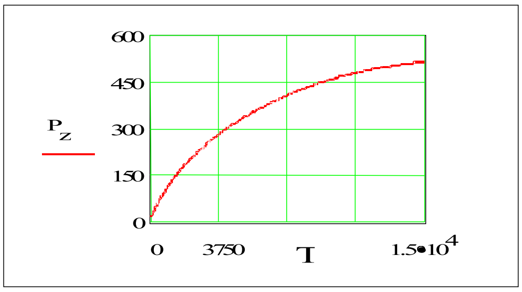

Fig.6

REFERENCES

1. V.A. Buts, A.V. Buts. Dynamics of the charged particles in a field of an intensive cross electromagnetic wave // *JETPh*, 1996, 110, N. 3 (9), p. 818-831.
2. A.V. Buts , V.A. Buts. Acceleration of plasma by a field of laser radiation // *Electromagnetic waves and electronic systems.* 2001, N 6, p. 50-56.
3. N.B. Baranova, M.O. Skalli, B.Ya. Zeldovich Acceleration of the charged particles by laser beams // *JETPh.(105).* 1994, N. 3, p. 469-486 .

ОСОБЕННОСТИ ДИНАМИКИ ЧАСТИЦ И ПОЛЕЙ ПРИ КРИТИЧЕСКИХ НАПРЯЖЕННОСТЯХ ЭЛЕКТРОМАГНИТНЫХ ВОЛН (ЧАСТЬ I)

В.А. Буц

Изложены некоторые результаты изучения динамики заряженных частиц в поле интенсивных электромагнитных волн. Исследованы интегралы и рассмотрены некоторые схемы лазерного ускорения. Показано, что наиболее эффективной схемой ускорения является схема, в которой используется лазерный импульс с круговой поляризацией. Показано, что силы радиационного трения могут способствовать передаче энергии от лазерного поля к частицам. Кроме того, показано, что для лазерного ускорения силы радиационного трения значительно менее существенны, чем в циклических ускорителях.

ОСОБЛИВОСТІ ДИНАМІКИ ЧАСТОК І ПОЛІВ ПРИ КРИТИЧНИХ НАПРУЖЕНОСТЯХ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ (ЧАСТИНА I)

В.О. Буц

Викладено деякі результати вивчення динаміки заряджених часток у полі інтенсивних електромагнітних хвиль. Досліджено інтеграли і розглянуто деякі схеми лазерного прискорення. Показано, що найбільш ефективною схемою прискорення є схема, у якій використовується лазерний імпульс із круговою поляризацією. Показано, що сили радіаційного тертя можуть сприяти передачі енергії від лазерного поля до часток. Крім того, показано, що для лазерного прискорення сили радіаційного тертя значно менш істотні, ніж у циклічних прискорювачах.