GENERATION OF FAST PARTICLE FLUXES BY FINITE AMPLITUDE ELECTROMAGNETIC WAVES IN SPACE PLASMA

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The numerical calculations are performed to determine the regions of problem parameters in which the charged particles trapping and their following surfatron ultrarelativistic acceleration occur. It has been obtained the complicated structure of these region, in particular, the capture islands may exist with ultrarelativistic acceleration of charges. In the case of plasma without external magnetic field the charges acceleration by the packet of finite amplitude electrostatic waves is investigated. The optimal choice of waves parameters has been substantiated which are favourable ones for the charges acceleration and correspond to the main parametric resonance realization in the wave-particle interaction. The dependence of acceleration dynamics on the wave phases distribution is studied.

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1. INTRODUCTION

The investigation of fast particle fluxes generation is of the great interest for space plasma physics, in particular, for the problem of cosmic rays hard component origin [1-3], to explain the suprathermal charges fluxes observed in the circumterrestrial space [4-6] and so on. One of the mechanisms of relativistic particle fluxes forming in the astrophysics is the surfatron acceleration of charges by electromagnetic waves in the magnetoactive plasma (see, for example, [7-9]). But to do the correct estimates of the accelerated particles number, their energy maximum and energy spectra it is necessary to determine the conditions of charges capture by wave for the following ultrarelativistic acceleration, namely the optimum values of charge velocity and the wave phase Ψ at the particle trajectory. This problem is solved below numerically. We do the computer simulations of charges surfatron acceleration by the finite amplitude electromagnetic wave propagating across the external magnetic field and the wave filed vortical component is taken into account. In particular, it has been founded that on the initial data plane (Ψ_0, a), where $a = (d\Psi/d\tau)_{(0)}$, the region of highly relativistic charge acceleration is multiple-connected one and may includes both the capture islands and charge untrapping subregions.

In the case of plasma without external magnetic field the regular nonlinear mechanism of charged particles acceleration by the wave packet including electrostatic finite amplitude modes is studied. Taking into account the dependence of electrostatic modes phase velocity on their wavenumber, it is determined the optimal choice of wave packet parameters for which the successive charges capture by modes with growing phase velocity and their following acceleration occur. The charge transitions between moving potential walls are conditioned by the parametric resonance interaction of particles and neighbouring modes with growing phase velocity. These interactions correspond to the nonlinear oscillator pumping by periodic external force. Wave amplitudes have a some distribution on the mode wavenumber. The computer simulation results are presented in graphic form including the phase plane of accelerated charges.

2. THE CHARGES CAPTURE TO REGIME OF HIGHLY RELATIVISTIC SURFATRON ACCELERATION IN THE MAGNETOACTIVE PLASMA

Let us consider the interaction of electrons with electromagnetic wave having the frequency ω and the amplitude E_0 which propagating across the external magnetic field $H = H_0 \cdot e_z$ directed along the axis z. The wave fields have components $E_x = E_0 \cdot \cos\Psi$, $E_y = \chi \cdot E_0 \cdot \sin\Psi$, $H_z = N \cdot \chi \cdot E_0 \cdot \sin\Psi$, where где $\Psi = \omega t - kx$, $\chi = \varepsilon_\perp / \varepsilon_c$. The parameter χ determines nonpotential (vortical) part of wave fields, $\varepsilon_\perp$ and ε_c are the plasma dielectric tensor components. For the problem of charges acceleration the nondimensional wave phase velocity β_p is $\beta_p = 1/N < 1$, where $N = ck/\omega$ is the refractive index and $N^2 = \varepsilon_\perp - \varepsilon_c^2/\varepsilon_\perp$. Using the nondimensional variables $\tau = \omega t$, $\beta = \upsilon / c$ the relativistic equations for the accelerated electrons are reduced to the following nonlinear, nonstationary equation for the wave phase at the accelerated particle trajectory

$$\frac{d^2\Psi}{d\tau^2} - \left[\sigma\left(1-\beta_x^2\right)/\gamma\beta_p\right]\cdot\cos\Psi - \frac{u\beta_y}{\gamma\beta_p} + \frac{\sigma\chi\beta_y\cdot(\beta_x - N)}{\gamma\beta_p}\cdot$$
$$\cdot\sin\Psi = 0, \qquad (1)$$

where $u = \omega_{He}/\omega$, $\sigma = eE_0/mc\omega$, $\omega_{He} = eH_0/mc$ is the electron gyrofrequency, $\beta_x = \beta_p \cdot \left[1 - (d\Psi/d\tau)\right]$. We have used two integrals of motion $J = \gamma\cdot\beta_y + u\cdot\beta_p\cdot(\Psi - \tau) - \sigma\cdot\chi\cdot\cos\Psi$ =const and $\gamma\beta_z$ = const. Here $\gamma = \left(1-\beta^2\right)^{-1/2}$ is the relativistic factor of electron accelerated. There are the following expressions for γ and β_y

$$\gamma = \left\{1 + g_z^2 + \left[J + \sigma\cdot\chi\cdot\cos\Psi + u\cdot\beta_p\cdot(\tau - \Psi)\right]^2\right\}^{1/2}\gamma_x$$

$$\beta_y = \left[J + u\cdot\beta_p\cdot(\tau - \Psi) + \sigma\cdot\chi\cdot\cos\Psi\right]/\gamma,$$

$$\gamma_x = \left(1-\beta_x^2\right)^{-1/2}.$$

The equation (1) was solved numerically with the initial data $\Psi(0)=\Psi_0$, $\Psi_\tau(0)=a$. The wave amplitude σ was taken to be above the threshold value $\sigma_c = u\,\gamma_p$ providing the charge capture by wave, where $\gamma_p = \left(1-\beta_p^2\right)^{-1/2}$.

Firstly, for the fixed value of wave phase velocity β_p we take the parameter $u = \omega_{He}/\omega < 1$ and then solve the equation (1) with initial data $\Psi(0) = \Psi_0$ from the following range $\Psi_0 \subset (-\pi/2,\ 3\pi/2)$ with the step $\delta\Psi_0$=0,01. The parameter u was varied in the interval (0, 1) with the step δu =0,01. The calculation results are shown in the Fig.1 for the case β_p = 0.575, a = 0, σ =1.1 σ_c.

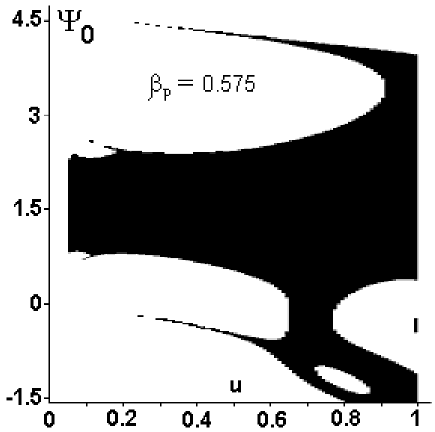

Fig.1. The region of charge capture by wave to the regime of highly relativistic surfatron acceleration

According to Fig.1 the region on the plane (u, Ψ_0) of charge capture by wave with the following highly relativistic acceleration (it is marked by the black color) has very complicated structure. It is the multiple-connected area. The islands of charge nontrapping are separated by the narrow regions in which the so-called unlimited acceleration occurs. Under the parameter β_p increase the number of nontrapping islands will decrease but the closed areas of unlimited acceleration appear and for the case β_p=0.99 the region of unlimited acceleration becomes single-connected (see Fig.2).

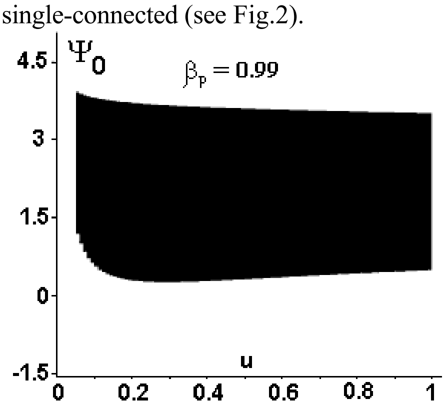

Fig.2. The case of single-connected region of charges capture by wave into the regime of unlimited surfatron acceleration

The phenomenon observed in our computer simulation means that the effective acceleration potential in equation (1) must have the higher harmonics like $\cos 2\Psi$, $\sin 2\Psi$, $\cos 3\Psi$ and so on.

It is of great interest to study the structure of region of charges capture into the regime of unlimited acceleration on the plane of initialal data (Ψ_0, a) under the fixed value of other parameters. It is obvious that for the parameter Ψ_0 the picture will be the periodical with the period 2π. The region of possible values of parameter $a = (d\Psi/d\tau)_{(0)}$ is determined from the condition $|\beta_x|$ <1. These calculations were performed and the case of parameters choice u=0.8, β_p=0.575, $\gamma\beta_z$=0 is presented in the Fig.3. We see again the the multiple-connected structure of the capture region.

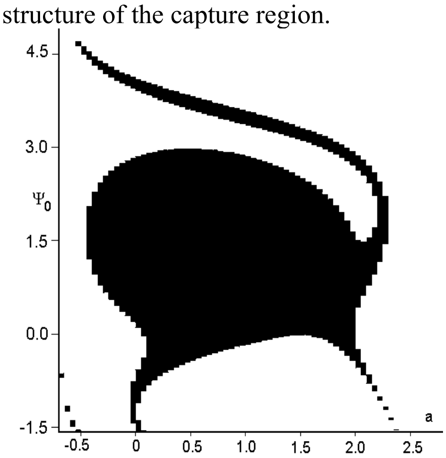

Fig.3. The structure of capture region on the initial data plane

The demonstrate the possibility of appearance of capture region multiple-connected structure we may consider the plott of effective potential

$$U_{eff}(\Psi) = 0.5\cdot\cos\Psi + 0.9\cdot\Psi + 1.3\cdot\cos 2\Psi + 1.1\cdot\cos 3\Psi$$

presented in Fig.4 with two region of the charges trapping and unlimited acceleration.

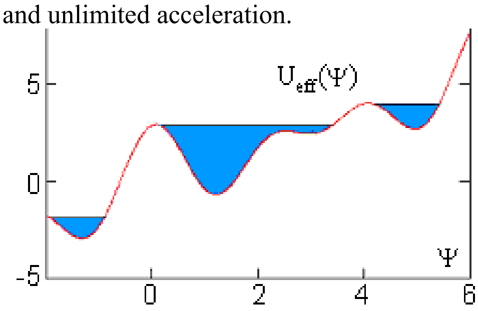

Fig.4. The plot of effective potential $U_{eff}(\Psi)$

It is possible to obtain other examples of the effective potential with multiple-connected region of particles capture by the finite amplitude electromagnetic wave and the following highly relativistic acceleration.

It is of interest to investigate the structure of capture region in the case of highly relativistic particles injection, for example, under the initial data choice $\gamma\beta_z >> 1$. The calculations performed for initial data with large particle impulse along the external magnetic field $\gamma\beta_z = 100$ and the electromagnetic wave with phase velocity β_p=0.8 have shown that for ultrarelativistic charges injection the capture region structure on the plane

(u, Ψ_0) becomes practically the single-connected one.

3. THE CHARGES ACCELERATION IN AN ISOTROPIC PLASMA BY THE FINITE AMPLITUDE ELECTROSTATIC WAVES PACKET

Let us consider now the charged particles acceleration by the wave packet to be the superposition of finite amplitude electrostatic modes. For 1D-problem the charge interaction with electrostatic waves is governed by the following equation

$$m\frac{d^2x}{dt^2} = qE_0 \sin(k_0 x - \omega_0 t + \psi_0) + \sum_n qE_n \cdot \sin(\Phi_n) - $$
$$- m\nu \frac{dx}{dt}, \Phi_n = k_n x - \omega_n t + \psi_n.$$

Here E_n, ψ_n are the wave amplitudes and their phases respectively, $\omega_n = \omega(k_n)$ are frequencies, $m\nu\, dx/dt$ is the friction force, $1 \le n \le N$. We suppose that under the mode number n increase the wave vector k_n will decreases but the wave phase velocity ω / k_n will grow. For example, such situation occurs for the langmuir wave having frequency $\omega(k_n) = \left(\omega_{pe}^2 + k^2 \upsilon_T^2\right)^{1/2}$, $\upsilon_T^2 = 3T_e / m$, where ω_{pe} and T_e are the electron langmuir frequency and temperature respectively.

Let us go to the reference frame moving with the phase velocity ω_0 / k_0 so $x(t) = (\omega_0 t / k_0) + y / k_0$ and suppose that at initial time $t = 0$ the charge velocity was close to ω_0 / k_0. Then it is necessary to introduce nondimensional variables and parameters like this $\tau = \omega_b t$, $a_n = E_n / E_0$, $\omega_b = (qk_0 E_0 / m)^{1/2}$, $q_n = k_n / k_0$, $\Omega_n = (k_0 \omega_n - k_n \omega_0) / k_0 \omega_b$, $\mu = \nu / \omega_b$, $\alpha = \mu \omega_0 / \omega_b$, where ω_b is the bounce-frequency of charge oscillations in the potential wall of the mode with frequency ω_0, the nonlinearity parameter is small $\delta = \left(qE_0 k_0 / m\omega_0^2\right) << 1$.

Finally we obtain the following equation describing the charge acceleration by wave packet

$$\frac{d^2 y}{d\tau^2} + \sin y = \sum_n A_n \cdot \sin(\Phi_n) - (\alpha + \mu y_\tau) \equiv f(y, \tau), \quad (2)$$
$$\Phi_n = q_n y - \Omega_n \tau + \psi_n.$$

The equation (2) describes the oscillator $y(\tau)$ motion in stationary potential wall $U_o = (1 - \cos y)$ under the action of external force $f(y,\tau)$. In the absence of $f(y,\tau)$ the oscillator energy $E = 0.5 \cdot y_\tau^2 + U_0(y)$ conserves and for particles, trapped into potential wall $U_0(y)$, their energy belongs to the following range $0 \le E \le 2$. So their velocities are in the range $|dy / d\tau|$ <2. The amplitudes A_n are determined by the wave packet spectrum.

In the numerical calculations the choice of mode parameters must satisfy to the second order parametric resonance. For example, the mode n =1 wave vector q_1 is obtained from the following condition $\Omega_1 \approx 2$. It means that the mode 1 will parametrically drives the oscillator and traps it into the moving potential wall U_1 after some time. After such trapping the mode 2 becomes the resonance one and will parametrically drives the oscillator. So after some time it will be trapped into the potential wall U_2 moving with the velocity Ω_2 / k_2.

This cascade process will be repeated again and results to the consecutive jumps of oscillator to the potential walls U_n with growing phase velocities Ω_n / k_n.

This scheme describes the regular mechanism of charges acceleration by the wave packet consisting from the finite amplitude electrostatic modes. It is in the principle, that for acceleration mechanism studied we must take into account the nonlinear particles dynamics in the each wave potential wall.

Results of numerical simulation of this acceleration mechanism are presented in Figs.5-7.

In these figures the curve $y(t)$ gives particle displacement and $r(t)$ is its asymptotics approximation after the charge capture by the mode with maximum phase velocity. We see that regular acceleration of charges due to their parametric interactions with wave packet containing the finite amplitude electrostatic mode is clearly observed in our numerical experiments. It is obvious that the number of modes in wave packet may be increased and significant growth of particles energy will be obtained.

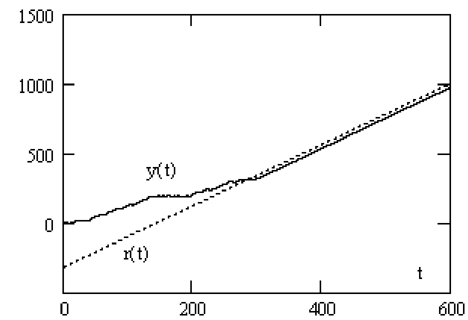

Fig.5. The charge trapping by the mode 1 due to the parametric resonance interaction.

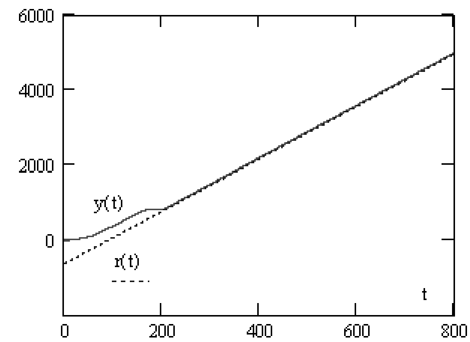

Fig.6. The charges acceleration by 4 modes wave packet

It is necessary to note that after charges trapping by the six mode the force conditioned by other 5 modes will be of the fastly oscillating one (see Fg.8, the curve f(t)). Because the particle is moving with velocity υ close to the mode 6 phase velocity the action this mode on the charge becomes slowly varying function (the curve f6(t) in the Fig.8.).

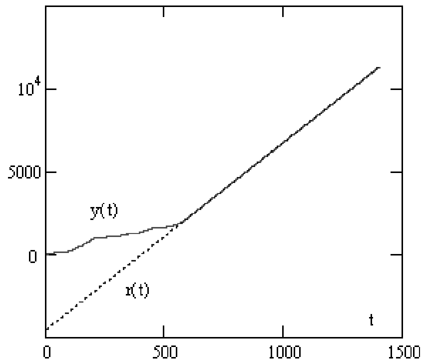

Fig.7. The charge acceleration by 6 modes wave packet

It is of interest to compare more clear the accelerated charge displacement under it forcing by the wave packet containing 2, 3, 4, 5 and 6 modes respectively.

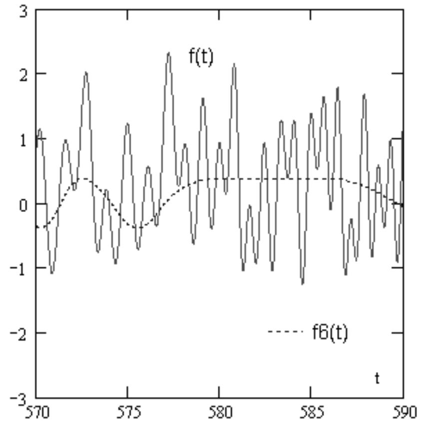

Fig.8. The plots of wave forcing f(t)

This situation is shown at the fig.9 by the plott of charge displacement $y(t)$ for the time interval $t \leq 3000$. The number under the curve suitable denotes the amount of electrostatic modes in the wave packet which accelerates the charge.

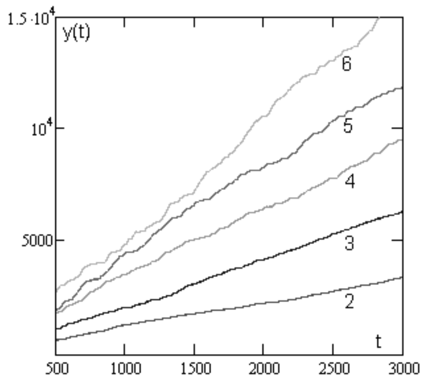

Fig.9. The charge displacement under acceleration it by 2, 3, 4, 5 and 6 modes

CONCLUSIONS

The results of this paper may be summarized as the following. Firstly, it was considered the charged particles acceleration by the finite amplitude electromagnetic wave propagating across the external magnetic field in the magnetoactive plasma (the surfatron mechanism of acceleration).

The structure of trapping region in the parameters space was studied by the computer simulation. The particles with parameters in the trapping region are captured by the wave and the following unlimited acceleration occurs. It has been shown that the capture region has very complicated multiple-connected structure. Which may be explained by the corresponding profile of the effective potential $U_{eff}(\Psi)$ in the governing nonlinear, nonstationary equation for the wave phase Ψ at the accelerated particle trajectory.

For the wave phase velocity close enough to the speed of light the structure of capture region becomes practically single-connected.

Secondly, the charged particle acceleration in the isotropic plasma by the wave packet containing the finite amplitude electrostatic modes with different phase velocities was considered numerically. This regular mechanism of charges acceleration is conditioned by the main parametric resonance of particles in the superposition of electric field of neighbouring modes. So the nonlinear dynamics of charge in the moving potential walls must be investigated.

The choice of self-consistent parameters of the wave packet modes (necessary to obtain the required charges acceleration) is described. The cascade process of the consecutive jumps of oscillating charge in the set of potential walls U_n moving with growing phase velocities Ω_n / k_n causes the regular mechanism of particles acceleration with significant charge energy growth.

The mechanism of charges acceleration studied gives the additional channel to generate the fast particle fluxes observed in the space plasma.

The investigation performed is of the interest for different branches of space plasma physics, in particular, for the problem of cosmic rays generation, to explain the suprathermal charges fluxes observed in the circumterrestrial space and so on.

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ГЕНЕРАЦИЯ ПОТОКОВ БЫСТРЫХ ЧАСТИЦ ЭЛЕКТРОМАГНИТНЫМИ ВОЛНАМИ КОНЕЧНОЙ АМПЛИТУДЫ В КОСМИЧЕСКОЙ ПЛАЗМЕ

Н.С. Ерохин, Н.Н. Зольникова, П.П. Гриневич, Л.А. Михайловская

Проведено численное моделирование для определения областей параметров задачи, в которых заряженные частицы захватываются и происходит их дальнейшее серфотронное релятивистское ускорение, в частности, могут существовать острова ультрарелятивистского ускорения зарядов. В случае плазмы без магнитного поля исследовано ускорение зарядов пакетом электростатических волн конечной амплитуды. Оптимальный выбор параметров волн, отвечающий приемлемым для ускорения зарядов условиям, соответствует реализации основного параметрического резонанса во взаимодействии волна-частица.

ГЕНЕРАЦІЯ ПОТОКІВ ШВИДКИХ ЧАСТИНОК ЕЛЕКТРОМАГНІТНИМИ ХВИЛЯМИ СКІНЧЕНОЇ АМПЛІТУДИ У КОСМІЧНІЙ ПЛАЗМІ

Н.С. Ерохін, Н.Н. Зольникова, П.П. Гриневич, Л.А. Михайловська

Проведено чисельне моделювання для визначення областей параметрів задачі, в яких заряджені частинки захоплюються та відбувається їх подальше серфотронне релятивістське прискорення, зокрема, можуть існувати острови ультрарелятивістського прискорення зарядів. У випадку плазми без магнітного поля досліджено прискорення зарядів пакетом електростатичних хвиль скінченої амплітуди. Оптимальний вибір параметрів хвиль, що визначає прийнятні для прискорення зарядів умови, відповідає реалізації основного параметричного резонансу у взаємодії хвиля-частинка.