STUDYING OF ELECTRONS SURFATRON ACCELERATION WITH A PACKET OF ELECTROMAGNETIC WAVES IN SPACE PLASMAS

N.S.Erokhin[1], N.N.Zolnikova[1], L.A.Mikhailovskaya[1], R.Shkevov[2]

[1]Space Research Institute of RAS, Moscow.
e-mail: nzolnik@iki.rssi.ru
[2]Space Research and Technology Institute (STRI) - BAS, Sofia
e-mail: shkevov@space.bas.bg

Abstract. In present paper the charged particles surfing is considered on the basis of numerical calculation of capture and following ultrarelativistic acceleration charges in magnetoactive space plasma under their interaction with smooth envelop of wave packet amplitude. The particles initial energy is assumed weakly relativistic. Wave package is propagating across the weak external magnetic field. In the central wave packet area the electric field amplitude is above of some threshold value. It was considered the dynamics of momentum components and velocity ones for accelerated charges, typical particularities of their trajectory with taking into account cyclotron rotation on initial stage, typical phase plane structure for investigated nonlinear equation are considered.

1. Introduction

Investigation of the processes resulting in generation of relativistic particles fluxes is one of the actual tasks of space plasma physics, in particular, it is of considerable interest for the problem of cosmic rays (CR) generation in astrophysics. This is due to the fact that charges surfing on the electromagnetic waves (which was discussed earlier, for example, in papers [1], [3], [4], [6], [7], [8]) is one of effective mechanisms for generation of ultrarelativistic particles fluxes. The analysis of favorable conditions for the charged particle captures by electromagnetic waves, the investigation of particle acceleration efficiency under the influence of finite amplitude spatially localized waves packet is a difficult enough task. The problem is multiparametric and to reveal the main features of charges surfing on the waves packets in space plasma, a very large amount of numerical calculations is necessary.

In this paper, on the basis of nonlinear numerical calculations, the capture of weakly relativistic charged particles, in surfatron acceleration mode by electromagnetic waves packet propagating in plasma across a weak external magnetic field $\mathbf{H_0}$ **is considered.** The case of weakly relativistic particles acceleration is discussed when the period of charges cyclotron rotation is relatively small. For wave amplitude above the threshold value on the available time intervals of numerical calculations (outside the range of wave initial phases on the particle trajectory favorable for immediate particle capture into surfing mode) the charge rotation in external magnetic field occurs. After some number periods of charge cyclotron rotation (tens, hundreds or more) the condition of Cherenkov resonance takes place and the wave phase on the particle trajectory becomes favorable for the charge capture by wave. Consequently particle capture occurs by waves packet, and charge ultrarelativistic acceleration takes place. Therefore, in the volume of particle impulses the size of region where charges capture by the electromagnetic wave takes place must be large enough.

These results are helpful for the interpretation of experimental data on relativistic particles fluxes in space plasmas. Charges surfing on the electromagnetic waves ([2], [9], 10]) can be a local source of ultrarelativistic particles generation in the vicinity of relatively quiet stars, such as solar heliosphere, and to provide local deviations of the cosmic rays recorded spectrum from the standard power scaling.

2. Task formulation and numerical calculation results

The starting point are relativistic equations describing the motion of a charged particle interacting with an electromagnetic waves. The wave phase velocity in the plasma must be less than the speed of light in a vacuum to provide the possibility of Cherenkov resonance with charged particle. It should be noted here that the surfatron acceleration mechanism is associated with the realization in magnetoactive plasma the Cherenkov resonance in the wave-particle interaction. So it is possible for p-polarized waves of upper hybrid resonance frequency having refractive index $N^2 = 1 - [v(1-v)]/(1-u^2-v) \equiv \varepsilon_f$ where ε_f is determined by the plasma dielectric permittivity components. An external magnetic field is directed along the z axis: $\mathbf{H}_0 = H_0\, \mathbf{e_z}$. Charges capture in surfing mode occurs for wave amplitudes above the threshold value $\boldsymbol{\sigma} \equiv e\,E / m\,c\,\omega > \boldsymbol{\sigma_c} \equiv u\,\gamma_p = u/(1-\beta_p^2)^{1/2}$, where $\beta_p = k\,c/\omega$. Let's consider a wave spectrum with a carrying frequency $\boldsymbol{\omega_0}$. The problem incoming parameters are: $u = \omega_{He} / \omega$, $v = (\omega_{pe} / \omega)^2$, where ω_{He} is cyclotron frequency of plasma nonrelativistic electrons, $\omega_{pe} = (4\pi e^2 n_0/m)^{1/2}$ is electron Langmuir frequency and n_0 is the plasma density. For the perpendicular wave propagation with p-polarization the fields components are E_x, E_y, H_z. The main component of wave packet electric field with the Lorentz spectrum may be written as

$$E_x(x,t) = \{ E_m / [1 + (\zeta / L)^2] \} \cos (\omega_0 t - k_0 x), \qquad (1)$$

where $\zeta = x - v_g(k_0) t$ and $L = 1 / k_p$ is a full width at half maximum for the localized wave packet, propagating with group velocity $v_g(k_0)$.

Let us introduce now the dimensionless time $\tau = \omega t$. The calculations and estimations have shown that vortical components of the wave fields E_y, H_z may be neglected and for the packet wave phase on the carrying frequency $\Psi_0(x,t) = \omega_0 t - k_0 x$ can be used the following nonlinear equation

$$\gamma \beta_{p0} d^2\Psi_0 /d\tau^2 - (1 - \beta_x^2) \cdot (e E_x / mc\omega_0) - u_0 \beta_y = 0, \qquad (2)$$

$\beta_{p0} = \omega_0 /ck_0$, $\gamma = (1 + h^2 + g^2)^{0.5}/ (1 - \beta_x^2)^{0.5}$, where $E_x(x,t)$ is given above, $eE_x / mc\omega_0 = \sigma / [1 + \zeta^2 / L^2]$, $g = \gamma(0)\beta_y(0)$ is initial particle impulse component along wave front and the integral of motion $J = \gamma \beta_y + u_0 \beta_{p0} (\Psi_0 - \tau)$ is taken into account. There exists second integral of motion $\gamma \beta_z = \text{const} \equiv h$. The charge velocity component β_x in (2) is given by the following expression $\beta_x = \beta_{p0} [1 - (d\Psi_0 / d\tau)]$.

We will show now the results of numerical calculations of the equation (2) for the following set of initial parameters of the task investigated now $h = 0.61$, $g = 0.91$, $\beta_{p0} = 0.7$, $u = 0.2$, $\sigma = 1.5\, \sigma_c$, $\sigma_c = u\, \gamma_p$, $\rho = 5\cdot 10^4$, $a = 0$, corresponding to the weakly relativistic initial energy of the charged particle $\gamma(0) = 2.136$.

The capture of the charge in surfing mode is depending of the initial phase value $\Psi(0) = - k_0\, x(0)$ and in very non-monotonic way. For most of the initial phases on the interval $-\pi < \delta\Psi(0) < \pi$ particles wave capture in acceleration mode occurs at relatively small times in comparison to the time of ultrarelativistic acceleration $\tau_{ac} \sim 105106$ which corresponds to an increase of charge energy on three-four orders of magnitude. For example, in the case $\Psi(0) = 8330\, \pi + 1$, capture of a particle by a wave packet occurs immediately. Plot of the phase of $\Psi(\tau) - \Psi(0)$ is shown on the Fig.1. The phase $\Psi(\tau)$ at particle trajectory is oscillating near the bottom of effective potential well. The particle

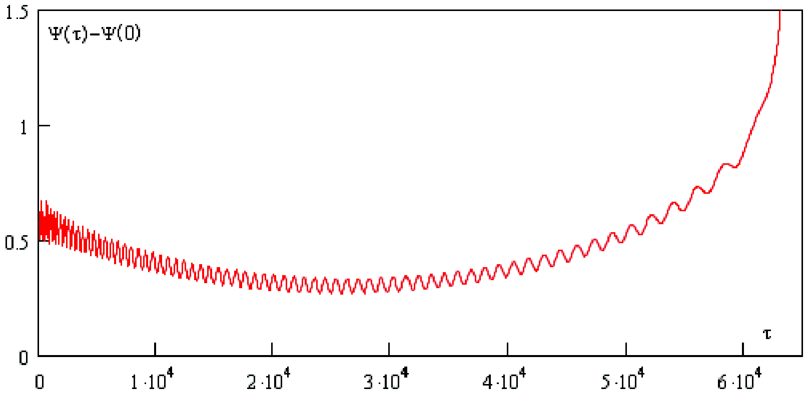

Fig.1.

becomes untrapped at time $\tau \approx 69200$ when it has arrived to the region where the effective potential well is absent. The displacement in the direction of wave packet propagation $\xi(\tau)$ for the trapped charge is practically linear function of time.

The plots of particle relativistic factor $\gamma(\tau)$ and its analytical approximation $M(\tau)$ are given on Fig.2. It is seen that the relativistic factor $\gamma(\tau)$ is very close to its analytical approximation $M(\tau)$. So it means that the trapped electron is accelerated by the spatially localized wave packet up to the energy 6.3 GeV with practically constant value of energy growth rate.

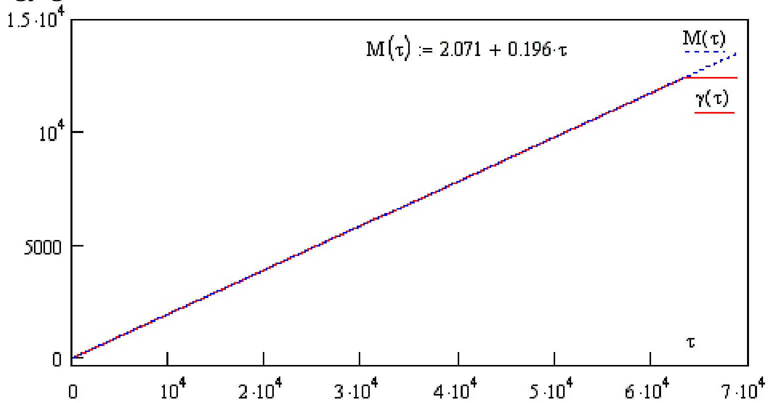

Fig.2.

The phase plane of accelerated particle ($\Phi(\tau)$, $\Psi(\tau)$ - $\Psi(0)$) , where $\Phi(\tau) = d\Psi(\tau)/d\tau$, is presented on Fig.3 . The trajectory on the phase plane is tending to a peculiar point, corresponding to a stable focus (the bottom of effective potential well), and a self-crossing of this curve is connected with the particle passage through maximum of wave packet field.

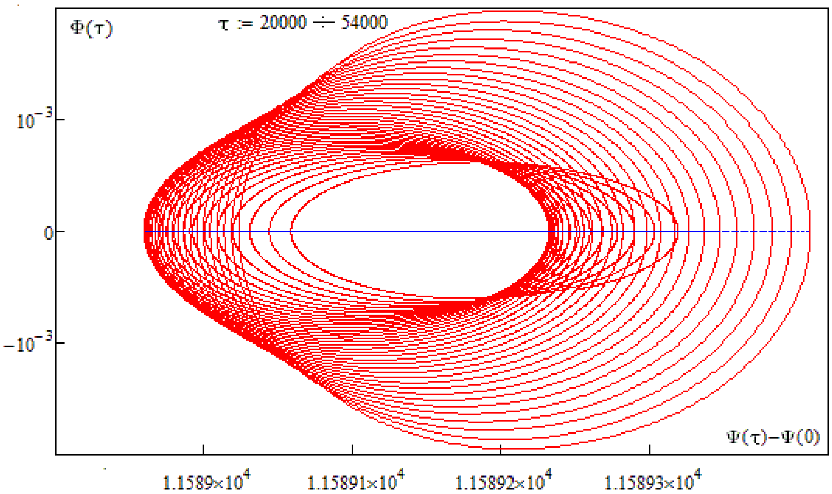

Fig.3.

3. Conclusion

Based on numerical calculations of nonlinear, nonstationary equation for the phase of wave packet on the carrying frequency, the strong surfatron acceleration of electrons was studied. The initial energy of particle is weakly relativistic. So the period of electron cyclotron rotation is relatively small in the comparison with a particle acceleration time and the number of charges captured to the surfing mode becomes larger. It is necessary to note here, that the increase of typical wave packet thickness L will results to more higher energies of accelerated particles at fixed value of field amplitude . Estimates have shown, that under electrons acceleration in the solar heliosphere, their energies may increase up to ten–hundreds GeV and more.

It has been shown that the capture to surfing mode for weakly relativistic particle happens for a wide enough range of wave initial phase (0) values on the particles trajectory and in presence of Cherenkov resonance deviation. For optimal conditions (the Cherenkov resonance presence and favorable wave initial phase Ψ (0) values) the capture of particles to surfing mode occurs immediately. Consequently, the number of weakly relativistic particle captured by the wave packet with the following ultrarelativistic acceleration can be large enough, due to strong increase in the initial velocity space region, from which the charges come into the surfatron acceleration mode.

The investigation of relativistic charges surfing on the electromagnetic waves is of great interest for space plasma physics. It can be useful also at interpretation of experimental data for relativistic particles fluxes registered in space conditions. In the vicinity of relatively quiet solar-type stars, the packets of electromagnetic waves may be a local source of cosmic rays generation with energies of tens-hundreds GeV. This phenomenon may explain differences between observed CR spectrums in this range and specified in the literature ones by power-law scaling.

This work was supported by Program P19 of Presidium of RAS.

References

[1]. S.V.Bulanov, A.S.Sakharov. JETP Letters, V. 44, No. 9, p.543,1986.

[2]. A.A.Chernikov, G.Schmidt, A.I.Neishtadt. Unlimited Particle Physical Review Letters, v. 68, № 10, p.1507-1510, 1992.

[3]. M.E.Dieckmann, P.K.Shukla. Plasma Physics and Controlled Fusion. 48, p.1515, 2006.

[4]. N.S.Erokhin, S.S.Moiseev, R.Z.Sagdeev. Astronomy Letters, Vol.15, № 1, p.3-10, 1989.

[5]. N.S.Erokhin, N.N.Zolnikova, E.A.Kuznetsov, L.A.Mikhailovskaya. Problems of atomic science and technology, Plasma Electronics and New Methods of Acceleration, V.4(68), p.116-120, 2010.

[6]. C.Joshi. Prospects and limitations. Radiation in plasmas, v.1, № 4, p.514-527, 1984.

[7]. N.Katsouleas, J.M.Dawson. Physical Review Letters, v.51, № 5, p. 392-395, 1983.

[8]. G.N.Kichigin. Journal of Experimental & Theoretical Physics, (JETP) Vol. 92, No.6, p.895, 2001.

[9]. R.Shkevov, N.S.Erokhin, L.A.Mikhailovskaya, N.N.Zolnikova, Journal of Atmospheric and Solar-Terrestrial Physics, JASTP, V.99 p.73–77, 2013.

[10]. V.M.Loznikov, N.S.Erokhin. Problems of atomic science and Technology, Plasma Electronics and New Methods of Acceleration, V.4(68), p.121-124, 2010.