RELATIVISTIC ELECTRONICS

THE HIGHLY RELATIVISTIC SURFATRON ACCELERATION OF ELECTRONS BY ELECTROMAGNETIC WAVE PACKET IN SPACE PLASMA

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On the basis of numerical calculations it is considered the highly relativistic surfatron acceleration of electrons in space plasma by spatially localized electromagnetic wave packet for the large initial energy of particles. The optimum conditions for strong electrons acceleration are formulated. The estimate of accelerated electrons maximum energy is given.

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INTRODUCTION

The analysis of processes resulting to generation of relativistic particles fluxes is among the actual problems of space plasma physics including, for example, the cosmic rays (CR) origin in astrophysics, their dependence on space weather conditions and for the correct interpretation of observation data. The surfatron acceleration (SA) of charged particles by electromagnetic waves is very effective mechanism of highly relativistic particle fluxes generation and it was studied early, for example, in papers [1 - 14]. It is necessary to note here that SA is conditioned by the Cherenkov resonance wave-particle in the magneto-active plasma which is possible for the p-polarization wave. Moreover the wave electric field amplitude must be above some threshold value. So the cyclotron rotation of trapped charge in weak external magnetic field is absent and this particle is moving in effective potential well under action of the accelerating electric field. The suitable electromagnetic waves for surfatron acceleration may have the frequency from the upper hybrid range. The detailed analysis of SA is necessary, for example, to obtain the corrected estimates of accelerated number particles, their energy spectra and typical scales of surfatron acceleration region in space plasmas. So it is necessary to investigate the most favourable conditions for electrons capture to the surfatron acceleration regime including the suitable initial wave phases at the particle trajectory, the efficiency of acceleration by wave packets and so on. This task requires a large enough volume of numerical calculations.

For the p-polarization wave propagation perpendicular to the external magnetic field the plasma refraction index $N^2 = (c\ k/\omega)^2$ for the upper hybrid frequency ω is: $N^2 = 1 - [v\ (1 - v)]/(1 - u^2 - v)$, $u = \omega_{He}/\omega$, $v = (\omega_{pe}/\omega)^2$, where $\omega_{He} = eH_0\ /m_e\ c$ – the nonrelativistic electron cyclotron frequency, $\omega_{pe} = (4\pi e^2 n_0/m_e)^{1/2}$ – the electron langmuir frequency, n_0 is plasma density.

Below we consider the case $u^2 << 1$ when the wave phase velocity is less the speed of light in a vacuum for the following values of parameter v: $1 - u^2 < v < 1$. The electrons capture to regime of surfatron acceleration takes place if the wave amplitude is above some threshold value when $\sigma \equiv e\ E_0/m_e\ c\omega > \sigma_c$, where parameter σ_c is $\sigma_c = u\ \gamma_p = u\ /(1 - \beta_p{}^2)^{1/2}$, $\beta_p = \omega/c\ k$.

According to previous analysis we may neglect the vortical components of waves field E_y, H_z in numerical calculations. The nonlinear effects of accelerating wave interaction with thermal plasma are also negligible under condition $\sigma^2 << 1$.

NUMERICAL CALCULATIONS RESULTS

Let us consider the relativistic equations for motion of electron with mass m_e under action of electromagnetic wave packet with Lorents envelope $E_x(x,t) = \{E_0\ /\ [1 + \zeta^2/\ L^2]\}\ \cos\ (\omega_0\ t - k_0\ x)$, where $\zeta = x - v_g(k_0)\ t$; $L = 1/k_p$ is the typical width of wave packet propagating across the external magnetic field with the group velocity $v_g(k_0)$; $2k_p$ is the typical scale of wave packet in k-space; $\beta_g = v_g/c << 1$; $\omega_0\ t - k_0\ x = \Psi(\tau)$. We use nondimensional time $\tau = \omega\ t$, coordinate along the direction of wave propagation $\xi = \omega\ x/c$, and the accelerated charge velocity $\boldsymbol{\beta} = \mathbf{v}\ /c$. By usage of the motion integrals $J = \gamma\cdot\beta_y - u\cdot\beta_p\cdot(\tau - \Psi)$, $h = \gamma\ \beta_z$ we have the following formula for the perpendicular impulse of accelerated electron $\gamma\ \beta_y = J + u\ \beta_p\ (\tau - \Psi) \equiv g$, the relativistic factor $\gamma = (1 + h^2 + g^2)^{1/2}/(1 - \beta_x{}^2)^{1/2}$ and the nonlinear equation for wave packet phase at the frequency ω_0 on the particle trajectory

$$\gamma\ \beta_p\ d^2\ \Psi\ /d\tau^2\ - Q\ \cdot\cos\ \Psi - u\ \beta_y = 0, \qquad (1)$$

$$Q \equiv \{\sigma\ /\ [1 + (\tau - \Psi)^2/\rho^2]\}\ (1 - \beta_x{}^2),$$

where $\rho = \omega\ L/c >> 1$. To determine the initial phases $\Psi(0)$, for which the electron capture by wave packet takes place with following ultrarelativistic acceleration we have fixed the problem incoming parameters β_p, $g_y(0) = \gamma(0)\beta_y(0)$, u, a, σ. The wave packet amplitude was taken above the threshold value namely $\sigma = 1.6\ \sigma_c$.

Then numerical calculations were performed for $\tau \le 40000$ to determine the initial phases corresponding to capture of electron be wave packet. Let us consider the calculation results for following choice of incoming parameters $h = 30$; $g_y(0) = 50$; $\beta_p = 0.9$; $u = 0.2$; $\sigma = 1.6\ \sigma_c$; $\sigma_c = u\ \gamma_p$; $a = 0$; $\rho = 5\cdot 10^4$ corresponding to high

$\gamma(0) \approx 133.791$ relativistic magnitude of initial electron impulse. The initial phase choice corresponds to the left part of wave packet $\Psi(0) = \pi \cdot 8330 + \delta\Psi(0)$, where $-\pi \leq \delta\Psi(0) \leq \pi$ and the step on $\delta\Psi(0)$ was small 0.1. According to calculations performed in the time interval of the order of $\tau_m = 6 \cdot 10^4$ capture of particle by wave packet takes place for about half of the $\delta\Psi(0)$ values and then particle is going on ultrarelativistic acceleration. For other values of $\delta\Psi(0)$ the particle capture wasn't observing in the time interval $\tau < \tau_m$. But for the few values of $\delta\Psi(0)$ the capture time was about $3 \cdot 10^4$ leading to significantly less the increase of particle energy.

The typical structure of trajectories on the phase plane $(\Phi, \delta\Psi)$, $\Phi = d\Psi/d\tau$ is given for $\delta\Psi(0) = 1.5$ in Fig. 1.

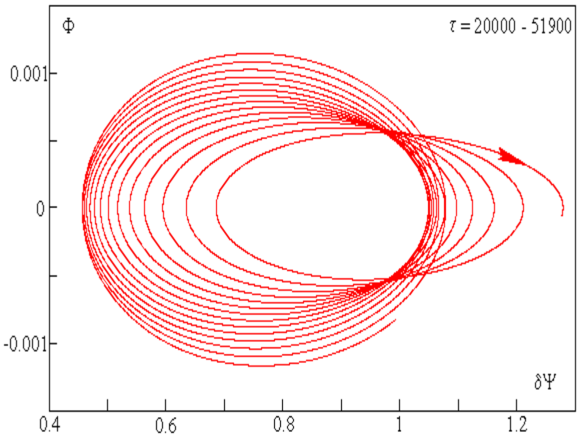

Fig. 1. Trajectories on phase plane (Φ, δΨ), δΨ(0) = 1.5 space

As it is seen, there is a movement of contracting spiral to a singular point of a stable focus type. After crossing the wave packet the representative point in the phase plane moves along the expanding spiral, which corresponds to the uncaptured particle. Similar results are obtained for other choice values $g_y(0)$ and h. It should be noted that due to the conservation of the components of particle momentum along the external magnetic field the longitudinal velocity of the captured particles β_z will decreases. The typical plot of phase on the particle trajectory is given in Fig. 2 for $\delta\Psi(0) = 1.5$.

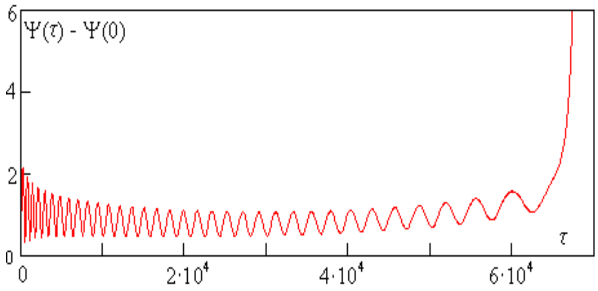

Fig. 2

It is interesting to note here that in the case of the initial phase choice $\delta\Psi(0) = 2.3$ for unchanged values of other incoming parameters the variations of phase $\delta\Psi(\tau)$ on the trapped electron trajectory are very small (see the temporal dynamics of $\delta\Psi(\tau)$ on the Fig. 3).

So the initial phase $\delta\Psi(0) = 2.3$ corresponds to the potential well bottom.

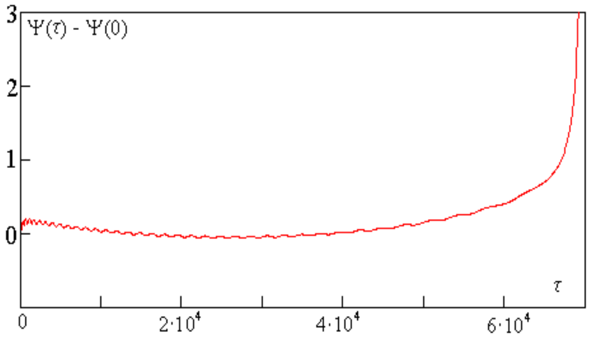

Fig. 3

The plotts of trapped electron relativistic factor $\gamma(\tau)$ and its analytical approximation $M(\tau)$ are presented in Fig. 4 for the time interval $\tau < 7.5 \cdot 10^4$.

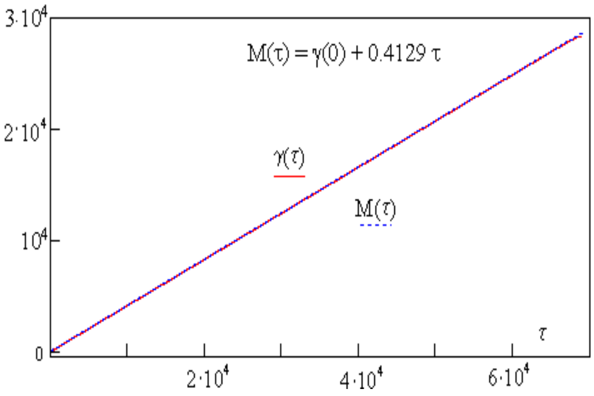

Fig. 4. Plotts of trapped electron relativistic factor γ(τ) and its analytical approximation M(τ)

According to Fig. 4 the trapped electron surfatron acceleration by the wave packet has practically the constant growth rate of particle energy. After electron detrapping from potential well its maximum magnitude of relativistic factor is $\gamma \approx 2.82 \cdot 10^4$ and the particle trajectory corresponds to the cyclotron rotation due to the external magnetic field.

According to calculations performed the transverse components of the trapped electron momentum in the surfatron acceleration regime are increasing with the constant growth rates since the transverse components of the trapped particle velocity go to the following asymptotic values $\beta_x \approx \beta_p$, $\beta_y \approx 1/\gamma_p = (1 - \beta_p^2)^{1/2}$.

CONCLUSIONS

This paper presents the results of numerical calculations of electrons capture into the surfatron regime acceleration by an electromagnetic wave packet having a smooth amplitude envelope Lorents type. It is shown that a maximum energy of trapped particles is proportional to the effective thickness of the wave packet in the space plasma and it can be quite large.

For relativistic initial electron energy the structure of area favorable (for particles capture into surfatron acceleration) initial values of the wave phase at carrier frequency becomes very simple and it is much easier to estimate the number of trapped particles and their effect on the attenuation of the wave packet during the surfatron highly relativistic acceleration.

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It is necessary to consider subsequent study surfatron acceleration of positrons by the wave packet in space plasmas including the geliosphere and local interstellar clouds. This task it is necessary to investigate also for larger values of initial energy of heavy nucleus like helium. In general, this task would require a very large volume of long-term numerical calculations. It is also important to note that the implementation of particles surfatron acceleration in space plasma should lead to variations of the CR fluxes which will depend on the presence of electromagnetic waves of sufficient amplitude that determined by the space weather conditions.

It is pissible to performed the estimates of accelerated particle energy in its maximum. For the conditions of space plasma such estimates gives the energy of particles in the range $10^3…10^6$ GeV.

It is important conclusion because such energies will be realized under conditions of absence of the extreme events like star explosuions.

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УЛЬТРАРЕЛЯТИВИСТСКОЕ СЕРФОТРОННОЕ УСКОРЕНИЕ ЭЛЕКТРОНОВ ПАКЕТОМ ЭЛЕКТРОМАГНИТНЫХ ВОЛН В КОСМИЧЕСКОЙ ПЛАЗМЕ

Н.С. Ерохин, Н.Н. Зольникова, Р. Шкевов, Л.А. Михайловская

На основе численных расчетов рассмотрено ультрарелятивистское серфотронное ускорение электронов в космической плазме пространственно-локализованным пакетом электромагнитных волн для больших начальных энергий частиц. Дана формулировка оптимальных условий для сильного ускорения электронов пакетом волн. Представлена оценка максимальной энергии электронов.

УЛЬТРАРЕЛЯТИВІСТСЬКЕ СЕРФОТРОННЕ ПРИСКОРЕННЯ ЕЛЕКТРОНІВ ПАКЕТОМ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ У КОСМІЧНІЙ ПЛАЗМІ

М.С. Єрохін, Н.М. Зольнікова, Р. Шкевов, Л.А. Михайловська

На основі чисельних розрахунків розглянуто ультрарелятивістське серфотронне прискорення електронів у космічній плазмі просторово-локалізованим пакетом електромагнітних хвиль для великих початкових енергій частинок. Сформульовано оптимальні умови для сильного прискорення електронів пакетом хвиль. Представлена оцінка максимальної енергії електронів.