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Numerical investigation of the surfatron acceleration efficiency of charged particles by wave packets in space plasma

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ABSTRACT

A theoretical study of the efficiency of the relativistic acceleration of charged particles by a finite amplitude electromagnetic wave packet in space plasma is presented. The effect of surfatron mechanism particle acceleration is investigated by numerical analysis of the second-order, non-stationary, nonlinear equation for the wave packet phase at the particle trajectory. The influence of the phase and group velocities of the wave packet at the wave packet carrying frequency on the acceleration efficiency is studied. The optimal conditions for weakly relativistic particles captured by electromagnetic wave packets with the following highly relativistic charge acceleration are determined. The particle energy growth rate for the regime of surfatron relativistic acceleration is determined. The temporal dynamics of particle acceleration are investigated. The conclusion about the possibilities of ultrarelativistic surfatron acceleration of charges by a wave packet with a smooth amplitude envelope is given.

1. Introduction

One of the efficient mechanisms for generating ultrarelativistic particle flows in space plasma, including cosmic rays, is charge surfing on electromagnetic waves, which is realized at the Cherenkov resonance with the accelerated particles (Katsouleas and Dawson, 1983; Joshi, 1984; Gribov et al., 1985; Bulanov and Sakharov, 1986; Sitnov, 1988; Erokhin et al., 1986, 1989, 1990, 2007). It is important to note, that in presence of external relatively weak magnetic field, the wave amplitude must be above a certain threshold. In this case for the charges appears efficient potential well where the trapped particles move. On average, these particles are located in the accelerating wave field.

In the present paper, the results of numerical calculations for trapped charged particles in magnetoactive space plasma are considered. These particles are ultrarelativistically accelerated by an electromagnetic wave packet with a smooth amplitude envelope. Taking into account the accelerated particle's constant of motion, the problem can be reduced to an analysis of the second order non-stationary, nonlinear equation of the dissipative type for the wave phase at the carrying frequency along the particle's trajectory. From the analysis performed, a correct estimation of the trapped particles number, their maximum energy and their possible energy spectrum may be determined.

The wave packet propagates across a weak enough external magnetic field. In the central part of wave packet, the maximum amplitude of electric field is above the threshold value. So, it is provided both the particles trapping by wave packet in an efficient potential well and their following strong surfatron acceleration.

The numerical calculations have confirmed that there exists an appropriate range of phases for surfing to occur. This range is wide enough at the wave-particle Cherenkov resonance that both the particle trapping and ultrarelativistic charge acceleration take place.

The energy of accelerated trapped particle is proportional to the region thickness, where the wave field intensity is above the threshold value. The ultrarelativistic particle's acceleration was studied for an initial particle kinetic energy of the order of $m_e c^2$. A smooth change of the wave amplitude is assumed.

The momentum component dynamics, a temporal behaviour of particles velocities and their trajectories are investigated. The trajectories analysis takes into account charges gyrorotation in the external magnetic field both before their acceleration by wave and after particles fly away from the efficient potential well. The dependence of acceleration efficiency from the initial value of problem parameters, including phase velocity of the wave is

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studied. The data processing and analysis for the ultrarelativistic particle fluxes in space plasmas has revealed a presence of an excess in some range of cosmic rays energy, depending on the space weather conditions. The possible reason for the deviation of the observed cosmic ray spectrum from the standard power law is considered. It is shown that the optimal condition for a realization of the charged particles maximum energy under surfatron acceleration occurs when the wave packet phase and group velocities are close to each other.

The investigation performed can be applied to experimental data concerning relativistic particle parameters in space, including the heliosphere, as well as to explain peculiarities in the observed cosmic ray spectrum.

2. Basic equations

Let us consider the acceleration of weakly relativistic electrons by an electromagnetic wave with p-polarization and a smooth Lorentz envelope amplitude, propagating along the x-axis in magnetoactive plasma across an external magnetic field H_o, which extends parallel to the z-axis. The wave frequency corresponds to the upper hybrid resonance. The phase velocity ω/k_x is less than the speed of light in a vacuum, and Cherenkov resonance with the accelerated particles becomes possible. Previously, it was shown that, for the numerical models, the set of the problem parameters may be taken as the following. The wave electric field is assumed to be electrostatic, i.e., $E(x,t)=E_x=A\cos\Psi$, where $\Psi=\omega t-kx$ and $A(x,t)$ defines the smooth Lorentz envelope of the wave amplitude. It is suitable to introduce nondimensional variables and parameters: $\boldsymbol{\beta}=\mathbf{v}/c$, $\sigma=eE_o/mc\omega$, $\tau=\omega t$, $\xi=kx$, $\gamma=1/(1-\beta^2)^{1/2}$—the particle relativistic factor, $u=\omega_{He}/\omega$, $\omega_{He}=eH_o/mc$ — the non-relativistic cyclotron frequency, E_o— the wave amplitude in the packet center and $\mu=eA/mc\omega$. Notice that $\beta_x=\beta_p\,[1-(d\Psi/d\tau)]$, $\beta_p=\omega/ck$ and the electron impulse is $\mathbf{p}=mc\gamma\boldsymbol{\beta}$. The relativistic equations of motion for the accelerated electron momentum can be written as

$$\begin{aligned} &d(\gamma\beta_x)/d\tau=-\mu\cos\Psi-u\beta_y\\ &\gamma\beta_z=const\equiv h\\ &d(\gamma\beta_y)/d\tau=u\beta_x\\ &d\gamma/d\tau=-\mu\beta_x\cos\Psi \end{aligned} \tag{1}$$

Using (1), the constant of motion for the accelerated electron is $J=\gamma\beta_y+u\beta_p(\Psi-\tau)$.

Taking into account J, the relativistic factor γ and the velocity components of the charge, β_y may be written as

$$\gamma=\left\{1+h^2+\left[J+u\beta_p(\tau-\Psi)\right]^2\right\}^{1/2}/(1-\beta_x^2)^{1/2}$$

$$\beta_y=\left[J+u\beta_p(\tau-\Psi)\right]/\gamma$$

The analysis of the charge acceleration, taking into account the Lorentz envelopes of the wave amplitudes, is performed on the basis resulting from (1) the nonlinear non-stationary equation for wave phase on the electron trajectory

$$d^2\Psi/d\tau^2-\left[\Lambda(1-\beta_x^2)/\gamma\beta_p\right]\cos\Psi-(u\beta_y/\gamma\beta_p)=0 \tag{2}$$

$$\Lambda=\sigma/\left\{1+\left[(\tau-\Psi)/\rho\right]^2\right\}$$

where $\rho=\omega L/c$, and L is the characteristic width at half maximum of a wave packet amplitude with a Lorentz envelope. To solve Eq. (2), the following initial parameters can be taken: $\Psi(0)=\Psi_0$ and $\Psi_\tau(0)=a$. According to these initial conditions, we have $\beta_x(0)=\beta_p(1-a)$. Let us introduce the components of the nondimensional particle momentum: $g_x=\gamma\beta_x$ and $g_y=\gamma\beta_y$. The threshold value of the nondimensional wave amplitude is $\sigma c=u\gamma_p$, where $\gamma_p=1/(1-\beta_p^2)^{1/2}$ is the relativistic factor of the accelerating wave packet. Charged particle trapping and acceleration occurs at a wave amplitude of $\sigma>\sigma_c$.

3. Charge surfing numerical calculation

The nonlinear Eq. (2) is solved numerically with conformity to the initial data. For a sufficiently long duration of charge acceleration, the numerical solution must approach the following asymptotes for components of the charge relativistic factor and its velocities: $\gamma(\tau)\approx u\beta_p\gamma_p\tau$, $\beta_x(\tau)\approx\beta_p$, $\beta_y\approx-1/\gamma_p$.

To find the initial range of phases $\Psi(0)$ where trapping of a charge occurs in surfatron acceleration, the phase velocity of the wave β_p is fixed, and the following condition is assumed: $0<\beta_p<1$. The wave amplitude was chosen slightly above the threshold level of σ_c, at $\sigma=1.57\sigma_c$. Then, by performing the numerical calculations over a comparatively short time interval, such as $\tau\sim25{,}000$, the range of initial phases were defined in which charge trapping by the wave package occurs in surfatron acceleration. The parameter $\rho=5\times10^4$ and a calculation interval of $0\le\tau<10^5$ was chosen because particle ejection from the trapping area occurred at times of 8×10^4.

Applying a set of initial parameters for the problem ($\beta_p=0.9$, $u=0.29$, $\sigma=1.57\sigma_c$, $h=0.31$, $g\equiv\gamma(0)$ $\beta_y(0)=0.41$, $\rho=5\times10^4$, $a=0$), the result of the calculations corresponds to a weakly relativistic charged particle with an initial energy of $\gamma(0)=2.652$. Some results are presented in Table 1 for the initial phases $\delta\Psi(0)$ and corresponding times τ_{tr}, where charge trapping by the wave occurs in surfatron acceleration. The initial position of the particle corresponds to the left border of the area, in which the wave field is higher than that in the threshold level. It was assumed that $\Psi(0)=\phi+\delta\Psi(0)$, where $\phi=2\pi\cdot5440$ and $|\delta\Psi(0)|<\pi$.

Table 1
Time trapping dependence from the initial wave phase $\Psi(0)$ on the particle trajectory.

$\delta\Psi_0$	3	2	1	0	−1	−2	−3	1.5	−1.5
τ_c	0	0	>25,000	>25,000	>25,000	>25,000	0	>25,000	>25,000
$\delta\Psi_0$	1.7	1.8	1.9	1.85	1.84	1.83	1.835	1.834	1.833
τ_c	>25,000	>25,000	0	0	0	>25,000	0	0	>25,000
$\delta\Psi_0$	2.5	0.5	−2.5	−0.5	−1.7	−1.8	−1.9	−1.85	−1.75
τ_c	0	>25,000	0	>25,000	>25,000	878	>25,000	>25,000	>25,000
$\delta\Psi_0$	1.3	1.4	1.35	1.2	1.15	1.1	1.05	0.8	0.25
τ_c	3453	>25,000	3212.6	3288	549	>25,000	>25,000	22,748	>25,000