STOCHASTIC HEATING OF CHARGED PARTICLES

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Comparison of two schemes of heating of charged particles is provided – at interaction with the field of wave with chaotically changing phase and with the field of the regular wave in the conditions of overlapping of non-linear resonances. Efficiency of heating at fulfillment of conditions of the resonances overlapping in all considered cases is more effective.

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INTRODUCTION

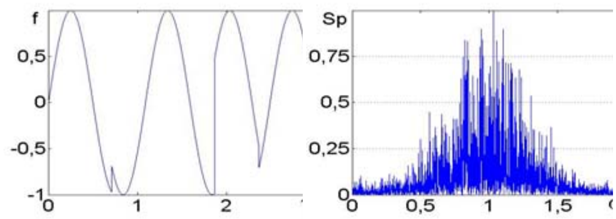
The heating of charged particles is one of the basic processes at realization controlled thermonuclear synthesis. Now there are two basic mechanisms of the heating: heating caused by interaction of charged particles with random electromagnetic field [1]; heating in the field of the regular wave when the dynamics of charged particles in such wave, is in mode of dynamic chaos [2,3]. Some schemes of the heating can be referred as combination of these two mechanisms. So, at plasma heating in magnetic traps interaction of charged particles with the field of wave occurs in narrow spatial domain. In this field the particles are in resonance with wave. Having transited this field, they get energy with high efficiency. The further dynamics of particles practically does not depend on electromagnetic wave presence. Being reflected from magnetic mirrors, charged particles get to the region of resonant interaction again. Multiple passage of particles of resonance regions leads to their heating. In such schemes of heating it is supposed that in trajectories from resonance region up to magnetic mirror and backward, the particle and the wave, in random way, change a phase relationship. The source of occurrence of randomness in most cases is not discussed. Implicitly it is supposed that the regime of the dynamic chaos is realized or fluctuations available in plasma are sufficient for such change. Probably, these two schemes can exist simultaneously.

The heating of plasma by the field with random characteristic has been sufficiently, in detail, studied in papers [4, 5]. In particular, there the attention to possibility of the plasma heating by the wave field which phase changed under the chaotic law, was paid. In paper [6] the plasma heating by the regular field of a laser radiation was considered, and has been shown that such heating is much more effective, than heating by random fields. However in this paper comparison was provided with delta-correlated noise field. In this case energy of wave is proportioned on very broad spectrum ("smeared"). In paper [4] we paid attention to the regular waves, which phases on the average for period changed in a random way. It was noticed that in this case energy of the wave is concentrated in a narrow spectrum. The analysis of the particles dynamics in the field of such waves specified on the efficiency of energy transmission of such waves to energy of charged particles. However the comparative analysis with efficiency of heating in modes with dynamic chaos was not carried out. In the present paper we give such analysis.

1. BUILD-UP OF WAVE WITH CHAOTICALLY JUMPING PHASE

For a base for formation of the wave with chaotically jumping phase, the travelling harmonic wave of kind $f(t,\vec{r}) = a\cos(\omega t - \vec{k}\vec{r} + \varphi_0)$ is taken (regular wave), to phase of which we will add stochastic function of time $\xi(t)$ with probability density having a uniform distribution $f(t,\vec{r}) = a\cos(\omega t - \vec{k}\vec{r} + \varphi_0 + \xi(t))$. For a numerical analysis the scheme of the numerical analysis which allows to vary the quantity of an interval of phases ($-\pi < \Delta\varphi_0 < \pi$) in which there is the jump of phase change, is realized. Also it is realized the possibility to select the interval of time in which, during the random moment of time, the phase jump occurs. Time of jump is supposed considerably smaller then the wave period.

On plots Fig. 1, as example, one can see the initial part of realization (length of 1000 period) of the wave field strength time dependence at random jump of the phase at each period of wave for interval of phases jump ($-\pi < \Delta\varphi_0 < \pi$) and spectral density of power of this realization. From these plots it is visible that phase jump

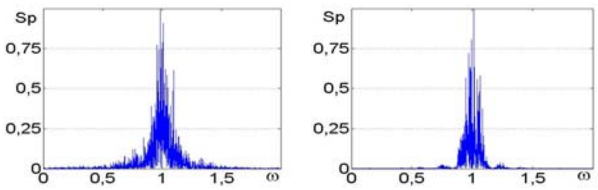


a *b*

Fig. 1. Field of wave and spectrum

occurs at random moment of time at each period of the regular wave Fig. 1,a, and quantity of this jump also is random and lies in the range of phases ($-\pi, \pi$). The spectrum (see Fig. 1,b) is widened enough with a maximum near to unity.

On plots Fig. 2 spectrums of wave with chaotically changing phase are given at various values of interval of time on which there is jumping of phase and quantity of interval of the phase jumps. One can see from these plots that, with increasing of the interval of time on which there is jump of the phase and reduction of an interval of the phase jumps, the spectrum of the wave is considerably narrowed.



a *b*

Fig. 2. Spectrum of wave.
a – single period with jump ($-\pi/2 < \Delta\varphi_0 < \pi/2$);
b – 5-th period with jump ($-\pi < \Delta\varphi_0 < \pi$)

Spectral bandwidth reduction is proportional both to reduction of quantity of jump, and increasing interval of time in which this jump takes place.

2. DYNAMICS OF PARTICLES IN THE FIELD OF WAVE WITH RANDOM CHANGING PHASE

Let's consider charged particle moving in the external magnetic field $\vec{H}_0$, guided along z axis and the field of plane electromagnetic wave with arbitrary polarization [2,3]. Equations of motion may be written in the form:

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

$$\dot{\vec{r}} = \vec{p}/\gamma; \; \dot{\psi} = \vec{k}\vec{p}/\gamma - 1,$$

where

$\tau \equiv \omega t,\; \vec{e} \equiv \vec{H}/H_0;\; \omega_H \equiv eH_0/mc\omega;\; \psi \equiv \tau - \vec{k}\vec{r} + \xi(\tau)$,

$\xi(t)$ - stochastic function changing under the law described above. Numerical modeling of the particle motion in the field of wave with chaotically changing phase is carried out in the absence of a magnetic field $H_0 = 0$ at various intervals of change of the phase jump ($-\pi < \Delta\varphi_0 < \pi$) and various intervals of time in which, at random moment, there is the phase jump. The parameter of the wave force has been chosen $\varepsilon = e\vec{E}_0/mc\omega = 1$.

On Fig. 3 time dependence of the energy change for single particle with initial phase $\psi_0 = 0$ and averaged on ensemble from 30 particles with initial phases from interval ($-\pi < \varphi_0 < \pi$) for case of single jump at period and interval of the phase jumps ($-\pi < \Delta\varphi_0 < \pi$), is presented. On the same plot, for comparison with the diffuse law of the energies growth with time, the curve of

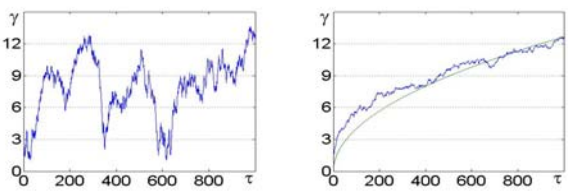


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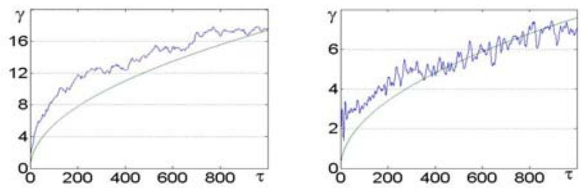
Fig. 3. Energy particle gain at the field.
a – one particle; b – ensemble averaging

the time dependence of the energy change is given: $\gamma_d(\tau) = \alpha\sqrt{\tau}$ at value of coefficient $\alpha = 0.4$.

From the Fig. 3,a one can see that single particle at interaction with field of wave in random way obtain and lose energy. However at ensemble averaging of particles (particle with various initial phases) certain regularity is observed.

On Fig. 4 plots of time dependence of the particles energy, averaged on ensemble of 30 particles for various values of the phases jump $\Delta\varphi_0$ are given.



a *b*

Fig. 4. Energy particle gain at the field with random jumping phase.
a – single period with jump ($-\pi/2 < \Delta\varphi_0 < \pi/2$),
b – 5-th period with jump ($-\pi < \Delta\varphi_0 < \pi$)

From plots Fig. 4 one can see that at ensemble averaging of particles the time dependence of middle energy has character close to diffused – smooth curves $\gamma_d(\tau) = \alpha\sqrt{\tau}$ with $\alpha = 0{,}55$ – plot 4,a and $\alpha = 0{,}25$ – plot 4,b. There is a certain optimum quantity of an interval of jumps of phase at which heating of particles is most effective.

3. DYNAMICS OF PARTICLES IN THE FIELD OF THE REGULAR WAVE IN THE CONDITIONS OF NON-LINEAR RESONANCES OVERLAPPING

Let's consider the dynamics of particles in the field of plane electromagnetic wave and in external constant magnetic field without random jumps of phase. This dynamics is described by the equations (1) at H_0 №0 and $\xi(t) = 0$. For maintenance of conditions of non-linear resonances overlapping, and also for the subsequent comparison of two methods of heating, parameter of the wave force is $\vec{\varepsilon} = 1$. In these conditions dynamics of charged particle, has stochastic character, with the characteristic random gain and loss of energy, Fig. 5,a. However, as well as in the case with phase jumps, the for ensemble averaged particles energy changes under the law

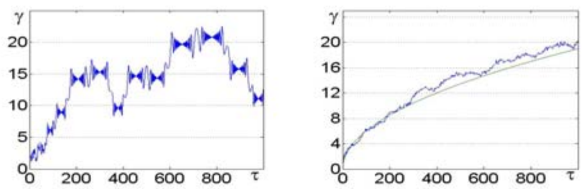


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Fig. 5. Energy particle gain at overlap resonances
a – one particle; b – ensemble averaging

close to diffusion low with coefficient $\alpha = 0.6$ (Fig. 5,b).

4. COMPARISON OF TWO MECHANISMS OF STOCHASTIC HEATING

At comparison of the heating mechanisms we will based with equality of amplitudes of waves in wave with jumping phase and in the regular wave $\varepsilon_R = \varepsilon_N$. In this case, as we saw above, the gain of energy by particles in such fields is approximately identical: $\Delta\gamma_R = \Delta\gamma_N$.

Energy of the noise wave: $W_N = \varepsilon_N^2 \Delta\omega_N$, $\Delta\omega_N \approx 0.4$

Energy of the regular wave: $W_R = \varepsilon_R^2 \delta\omega_R$, $\delta\omega_R \sim 1/Q$, $Q -$ quality factor . As $1/Q = 10^{-2}...10^{-7}$, higher level of energy of wave is necessary for achievement the same level of the particles energy in the field of wave with jumping phase. Greater efficiency of heating of charged particles by field of the regular wave in the conditions of overlapping of non-linear resonances is caused by narrow spectral line of such radiation, and also presence of cyclotron resonances. It is possible to expect that at particle motion in the field of regular waves in the conditions of cyclotron resonances presence of rare random jumps, even without overlapping of non-linear resonances, will be also effective. In this case the spectrum is narrowed. The particle moves in an intensive field. Preliminary investigations of such dynamics of particles really show the efficiency of this scheme of heating. Let's notice that such scheme of heating is similar to the scheme of heating of particles in magnetic traps. Efficient difference is the long-term motion of particles in synchronism with wave (resonances) at which the gain of velocity of particles is proportional to time of resonant interaction with field. Short jumps in this case play a role of the phase of particle loss, relatively to the wave at motion from mirror to mirror in traps.

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СТОХАСТИЧЕСКИЙ НАГРЕВ ЗАРЯЖЕННЫХ ЧАСТИЦ

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Проведено сравнение двух схем нагрева заряженных частиц – при взаимодействии с полем волны со случайно изменяющейся фазой и с полем регулярной волны в условиях перекрытия нелинейных резонансов. Во всех рассмотренных случаях эффективность нагрева при выполнении условий перекрытия резонансов оказывается более высокой.

СТОХАСТИЧНЕ НАГРІВАННЯ ЗАРЯДЖЕНИХ ЧАСТИНОК

В.О. Буц, В.В. Кузьмін, О.П. Толстолужський

Проведено порівняння двох схем нагрівання заряджених частинок – при взаємодії з полем хвилі з фазою, що випадково змінюється, та з полем регулярної хвилі в умовах перекриття нелінійних резонансів. У всіх розглянутих випадках ефективність нагрівання під час виконання умов перекриття циклотронних резонансів виявляється більш високою.