PARTICLE DIFFUSION IN A WAVE WITH RANDOMLY JUMPING PHASE

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Microwave radiation with random phase jumps attracts attention because of its ability to penetrate into the overdense plasma. Along with this the wave with jumping phase is involved into the resonance interaction with more particles than a regular wave, and can be used to accelerate and heat them. The evolution of statistical characteristics of particle ensemble in a wave is calculated numerically for two types of phase jumps, namely, when they are formed in the region of wave interaction with the particles, and when the wave with already generated phase jumps is launched into the interaction region. It is shown that the intensity of heating depends substantially on the type of phase jumps.

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INTRODUCTION

Microwave radiation with phase jumps was observed in experiments, and it is of considerable interest because of the ability to penetrate overdense plasma. It can be used to heat plasmas, in particular in discharges that are considered as promising sources of light radiation of the solar spectrum [1, 2]. On the other hand, sudden changes of a wave phase may occur due to nonlinear effects in plasma. They will influence the diffusion of particles in coordinate and velocity space.

Direct numerical simulation is used to study the behaviour of particles in a wave with random phase jumps. Two types of jumps are considered. First, when the phase jumps occur just in the plasma medium where the wave interacts with the particles. Then the frequency of jumps in a coordinate system moving with a particle does not depend on its velocity (uniform phase jumps). Second, when the wave with already jumping phase is launched into the plasma. Then frequency of jumps in the moving coordinate system decreases as particle velocity approaches wave phase velocity (slowing phase jumps) by analogy with the Doppler effect.

1. MODEL

We consider the motion of an ensemble of noninteracting particles in a field of the wave

$$E\cos(\omega_0 t - k_0 x + \varphi(t)), \qquad (1)$$

where E is the amplitude of the wave, ω_0 and k_0 are the frequency and the wave number, t and x are time and coordinate, $\varphi(t)$ is the phase of the wave, which varies with time by random jumps. A unique set of random phase jumps is prescribed to each particle from an ensemble.

Two types of phase jumps are considered. First type is characterized by constant probability p of a phase jump in the end of each period. In simulation we take p=0.2; the value of a phase jump is distributed with equal probability within the interval (0, 2π).

Second type of phase jumps is characterized by variable in time probability $p(t)$. It decreases as particle velocity averaged over fast oscillations $<v(t)>$ approaches phase velocity of the wave $p(t) = p\left|1-(k_0 <v(t)> /\omega_0)\right|$.

2. RESULTS OF SIMULATION

The results of simulation are shown in Figs. 1-6. Statistical characteristics of the ensemble of particles undergoing a wave field with random phase jumps were obtained from calculations of trajectories of 10^4 particles. In all plots length is normalized to $(2\pi/k_0)$ and time to $(2\pi/\omega_0)$. The magnitude of the electric field in this calculation corresponds to the amplitude of velocity oscillation of trapped particles which makes 0.141 of the wave phase velocity. And for the initial velocity of particles we took value 0.85. Note that particles with such initial velocity are not trapped by harmonic wave without phase variation, i.e. they would be non-resonant for regular wave.

If a wave phase is jumping then particles come into resonance interaction in a wider range of initial velocity. Eventually their bounce averaged velocity tends to phase velocity of a wave for both types of phase jumps. Thus particles with an initial velocity less than the phase velocity are accelerated, and for our initial condition particle averaged velocity increases from 0.85 to 1. The mechanism of this acceleration is similar to the stochastic Fermi acceleration. Along with acceleration stochastic heating of particles occurs, its measure is velocity dispersion. Note, that the growth of dispersion with time for the first type of phase jumps, which probability remain constant, is significantly greater then for the second type of phase jumps, which probability drops in accordance with the Doppler effect.

Bounce averaged velocities of ten arbitrary particles in a wave with phase jumps of the first and second types are shown in Figs. 1, 2. If the frequency of phase jumps is slowed down according to the Doppler effect (second type of jumps, Fig. 2) then particles wandering occurs mainly in a constricted region of phase space. Consequently coordinate and velocity dispersion is less than for the first type of jumps (see Fig. 1). Also for the second type of jumps is noticeable a fraction of particles, individual velocity of which tends to phase velocity of the wave.

Such behaviour of individual particles corresponds to spreading of the velocity distribution function shown in Figs. 3, 4 for three instants in time equal to 200, 10^3 and 10^4 periods. In a wave with constant probability of jumps the velocity distribution function is considerably expanded (see Fig. 3) that means that intensive heating process continues throughout the simulation time. In contrast with that for the second type of phase jumps the distribution function of particle velocity, after the initial expansion, almost keeps its shape (see Fig. 4).

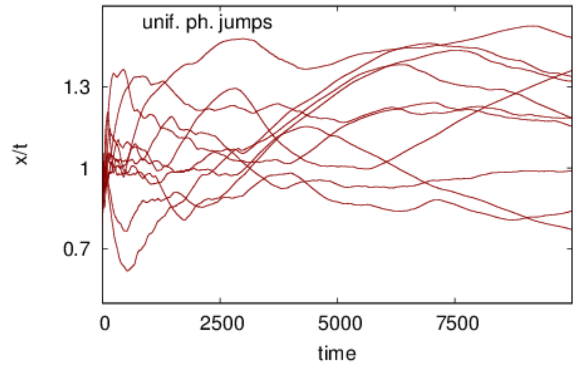

Fig. 1. Ten trajectories in velocity space for uniform jumps of phase (first type of phase jumps)

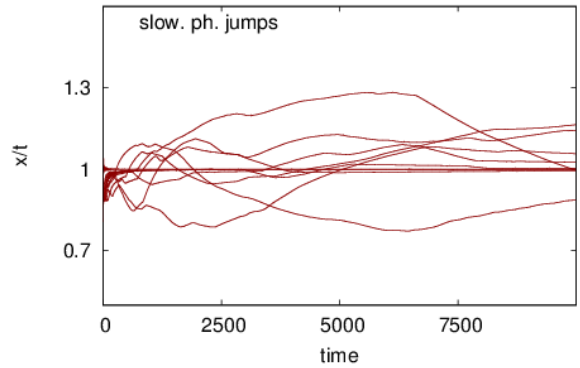

Fig. 2. Ten trajectories in velocity space for slowing jumps of phase (second type of phase jumps)

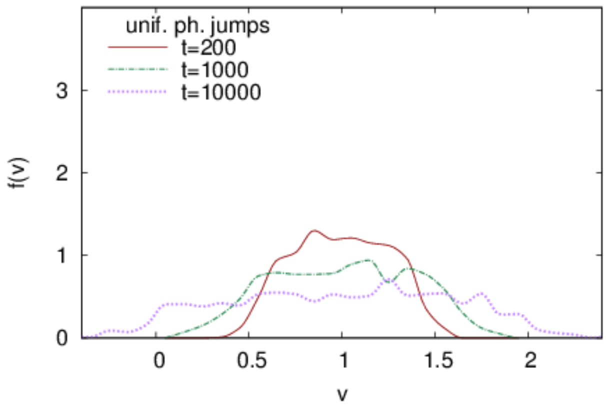

Fig. 3. Distribution function in velocity space for uniform jumps of phase

In process of expansion of velocity distribution function for both types of phase jumps more particles leave the velocity interval of resonant interaction than get into it from a non-resonant region.

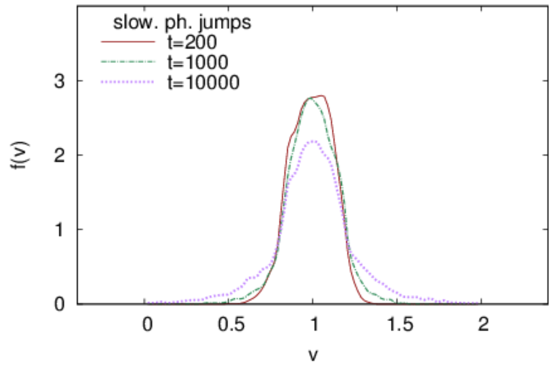

Fig. 4. Distribution function in velocity space for slowing jumps of phase

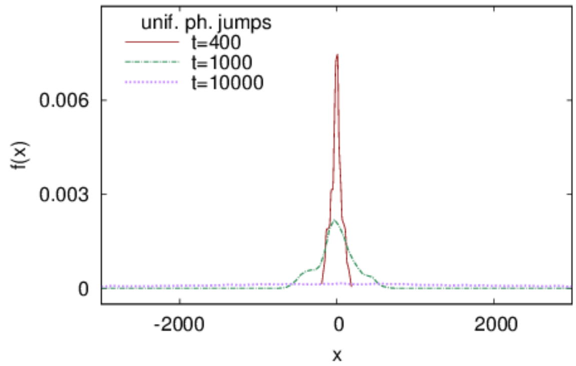

Fig. 5. Distribution function in coordinate space for uniform jumps of phase

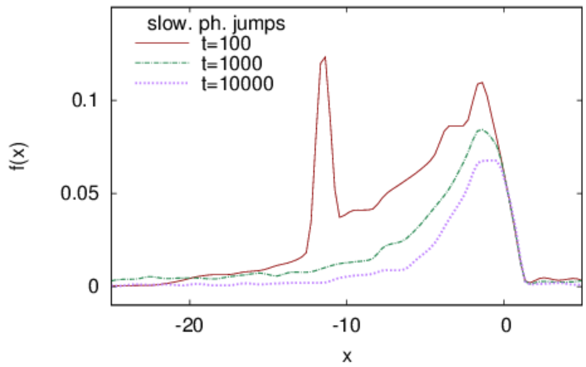

Fig. 6. Distribution function in coordinate space for slowing jumps of phase (space scale is smaller in compare with Fig. 5

The evolution of the particle distribution functions in coordinate space is given in Figs. 5, 6, where its shape is shown for three instants in time. Note that the spatial scales on these two figures for two types of phase jumps are very different. Spreading of the coordinate distribution function for the first type of phase jumps (see Fig. 5) are even more apparent than spreading of the corresponding velocity distribution function (see Fig. 3). In Fig. 6 we can see the peak of the coordinate distribution function for the second type of phase jumps at t = 100, it keeps the memory of the initial conditions, when all the particles were at one point of the phase space. It dissipates with time, however in overall this distribution function retain its shape much better than its counterpart given in Fig. 5.

CONCLUSIONS

Experimental observations show that intense wave in a plasma is characterized by a certain irregularity, which can be considered as random phase jumps. We drawn attention to strong dependence of the resonant particles behaviour on the way in which phase jumps occur. If phase jumps are formed during the interaction of the wave with particles, a probability of jumps in the coordinate system moving with the particle does not depend on its velocity. If the wave with phase jumps was generated earlier and then was launched into the interaction region, a probability of jumps in the moving coordinate system depends on particle velocity.

Simulation shows that due to jumps of a wave phase particles within a wider range of initial velocity, than it would be for harmonic waves without phase variation, are involved in the resonant interaction. In particular, particles with an initial velocity less than the phase velocity of the wave are accelerated. If the jumping phases are formed during acceleration, frequency of jumps in the coordinate system moving with the particle does not depend on velocity. Because of this, expansion of the particle distribution function in velocity and coordinate space continues permanently, respectively the dispersion of velocity is increased, and particles are heated.

If particles interact with a wave whose phase change is already formed they do not so much affected by jumps of phase while their velocities approach to phase velocity of the wave, and field for them looks similar to the field of harmonic waves without phase jumps. Consequently their acceleration is not accompanied by a significant increase of dispersion.

ACKNOWLEDGEMENTS

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ДИФФУЗИЯ ЧАСТИЦ В ВОЛНЕ СО СЛУЧАЙНО ПРЫГАЮЩЕЙ ФАЗОЙ

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Интерес к микроволновому излучению со случайными прыжками фазы обусловлен его способностью проникать в плазму с закритической плотностью. Кроме того, волна с прыжками фазы вступает в резонансное взаимодействие с бо́льшим количеством частиц, чем регулярная волна, и может быть использована для их ускорения и нагрева. Методом численного моделирования рассчитана эволюция статистических характеристик ансамбля частиц в поле волны для двух типов прыжков фазы, а именно: когда они образуются в области взаимодействия волны с частицами и когда волна с уже сгенерированными прыжками фазы вводится в область взаимодействия. Показано, что интенсивность нагрева частиц существенно зависит от типа прыжков фазы.

ДИФУЗІЯ ЧАСТИНОК У ХВИЛІ З ВИПАДКОВИМИ СТРИБКАМИ ФАЗИ

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Інтерес до мікрохвильового випромінення з випадковими стрибками фази обумовлений його здатністю проникати в плазму із закритичною густиною. Крім того, хвиля зі стрибками фази вступає в резонансну взаємодію з більшою кількістю частинок, ніж регулярна хвиля, і може застосовуватись для їхнього прискорення та нагрівання. Методом числового моделювання розраховано еволюцію статистичних характеристик ансамблю частинок у полі хвилі для двох типів стрибків фази, а саме: коли вони утворюються в області взаємодії хвилі з частинками і коли хвиля із вже згенерованими стрибками фази вводиться в область взаємодії. Показано, що інтенсивність нагрівання частинок істотно залежить від типу стрибків фази.