

THE PECULIARITIES OF STOCHASTIC HEATING OF THE PLAZMA IN PLASMA RESONATOR

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The results of the investigation of the dynamics of particles and waves at the interaction of intense electromagnetic pulses with plasmas are presented. It is shown that under conditions when regimes with dynamic chaos for wave-particle and wave-wave interactions are realized, there are still some correlation processes. They occur in the appearance of electromagnetic bursts that occur after sufficiently long time after the pulse, which acts on the plasma. In addition, the shape of instantaneous spectra of oscillations in plasma has a line structure.

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INTRODUCTION

The interaction of intensive electromagnetic pulses with a plasma can be divided into two main processes. This is a wave-particle interaction and a wave-wave interaction type. Each of these processes for certain values of the parameters can be either regular or stochastic. At the same time the regimes with dynamic chaos (stochastic processes) are considerably interesting for plasma heating. In our previous papers [1-3] the regular regimes and the regimes with stochastic dynamics of plasma particles at wave-particle interaction were studied. The high efficiency of heating of the plasma due to the overlap of non-linear combinational and cyclotron resonances was shown. The heating was very fast. Existing experimental conditions made it impossible to measure the time of heating. Theoretical estimations and experimental results were in good agreement. It was assumed the development of the global stochasticity and the complete absence of correlations at plasma particles motion. The second important point for plasma heating is the process of wave-wave interaction. This process develops at times much larger than the process of wave-particle interaction. It was also studied [4-10]. The conditions of occurrence of the regime with dynamic chaos were found. At the same time, as well as at wave-particle interactions, it was supposed that no correlation processes do not exist at these regimes.

However, the more rigorous experimental study of these processes has shown that there are condition when, despite the development of a global stochastic instability in these processes, there is some correlation effects. Below, we will briefly describe some of them.

1. INVESTIGATION METHODS

The more detailed description of the facility, which we use for investigations is presented in [8]. The main element of the experimental facility is a multimode cylindrical cavity with diameter of 16, 65 cm long, made of copper, placed in a longitudinal magnetic field (0.09...0.13 T on the resonator axis) of mirror configuration. The distance between the mirrors was set 43.7 and 44 cm, and mirror ratio was equal to 1.26 or 1.28,

respectively. The center of the resonator coincides with the center of the magnetic trap. The initial plasma was produced by ionization of the gas (argon) at pressure $(3...9) \cdot 10^{-2}$ Pa with an electron beam (beam diameter 1.8 cm, the energy was 600 eV, 80 mA). The plasma density degree was $10^9...10^{10}$ cm⁻³, the temperature degree was 10 eV. For excitation of the field in the resonator, the magnetron generator with capacity up to 1 MW and duration up to 2 microseconds was used. The resonator is excited at frequency of 2.77 GHz.

2. THE MAIN RESULTS AND DISCUSSION

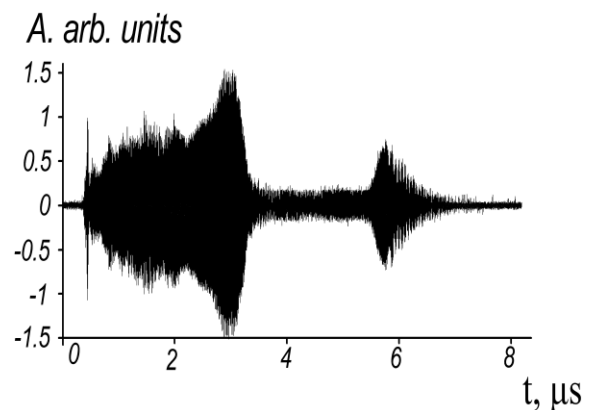


Fig. 1. The typical form of electromagnetic burst

The most important and unexpected correlation effect with the pointed above parameters of the facility is the appearance of additional electromagnetic bursts that appear after a certain time after the pulse ending from the magnetron. The typical form of electromagnetic burst is shown in Fig. 1. The time and the frequency of repeated pulses is random. Almost simultaneously with the microwave oscillations, the oscillation in optical and in X-ray spectrum are registered. The statistics of their occurrence is presented in Fig. 2. Even a small increasing of the mirror ratio increases the occurrence of the repeated oscillations and their frequency.

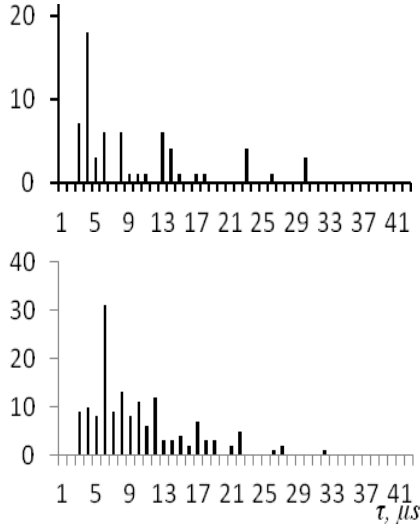


Fig. 2. The frequency of repeated X-ray pulses as a function of the mirror ratio of the guiding magnetic field. Diagrams from top to bottom - the mirror ratio 1.26 and 1.28, respectively

To explain the occurrence of such electromagnetic bursts of we considered three mechanisms that can manifest themselves in the specified conditions. First of all, the cyclotron instability can develop. The increment of this instability can be represented as:

$$\Gamma = \frac{\pi^2 \omega_p^2 v_{\perp}^3}{2ck\omega^2 n_0} \left[\frac{\omega_H}{3k_{\square}} \left\langle \frac{\partial f_0}{\partial v_{\perp}} \right\rangle + \frac{v_{\perp}}{4} \left\langle \frac{\partial f_0}{\partial v_{\square}} \right\rangle \right]. \quad (1)$$

The analysis of this expression shows that in order to explain the mechanism of occurrence of the bursts it is necessary to keep the distribution function of the particles almost constant ($\langle \partial f / \partial v \rangle \sim 10^{-4}$). Neither theoretical nor experimental results do not support such an assumption. The second mechanism that could explain the appearance of bursts is similar to those that appear in Fermi-Pasta-Ulam model. In order to let this mechanism to be realized, it is necessary that in the nonlinear interaction involving more than a hundred eigen modes of plasma resonator. This mechanism we discussed [6]. It should be noted that the bursts occur only when the magnetic field in which the plasma exist is non-uniform. Moreover, it is a trapping configuration. In such nonuniform field, not all plasma electrons are in the cyclotron resonances with an external electromagnetic pulse. Therefore, one could expect the saving of some correlations in the dynamics of the plasma electrons. However, the most likely mechanism for the bursts appearance is the effect of plasma echo. In order to understand and evaluate the possibility of its occurrence, let consider a simple ballistic model of a plasma echo. We suppose that the pulse of electromagnetic radiation influences on a plasma in a magnetic trap at $z = 0$. By the end of the pulse, the distribution function of the electrons in the plasma will follow the equation:

$$\frac{\partial f}{\partial t} + \vec{v} \frac{\partial f}{\partial \vec{r}} - \omega_H \frac{\partial f}{\partial \varphi} = 0 \quad (2)$$

It is easy to see that the solution of this equation can be written as:

$$f = f_0(\vec{v}, \vec{E}) \exp \left[-i\omega(t - \frac{\vec{r}}{4\vec{v}} + \frac{\varphi}{4\omega_H}) \right], \quad (3)$$

where $f_0(\vec{v}, \vec{E})$ – the amplitude of the perturbation of the distribution function under the influence of an electromagnetic pulse acting on the plasma. Distribution function (3) can be interpreted as a set of modulated beams. It can be seen that with increasing distance from the point of excitation from external disturbance pulse, the distribution function spreads. In this case, the charge density $\rho = \int f \cdot d\vec{v}$ will decrease rapidly with the increase of the distance. Note that in this case, the wavelength of the microwave-momentum is of order of 10 cm, and the electron Larmor radius is much smaller ($r_L \ll \lambda \sim 10cm$). In this case the spreading of the electrons in the transverse direction hardly occurs. Therefore, the main role is played by spreading in the longitudinal direction (axis direction z). The electrons reflected from the mirrors will move to the starting point of the perturbation, i.e. to the point $z \rightarrow 0$. In this case the fast phase variable in the expression under the integral for density charge ceases to depend on the rate of:

$$\rho = \int f_0 \exp \left[-i\omega(t + \frac{z}{4v_z}) \right] \cdot dv_z. \quad (4)$$

This is how we can explain the appearance of the echo signal. To reconcile the considered simple echo model with the experimental results, we must assume that the longitudinal velocity of the plasma electrons must be less then $2 \cdot 10^7 cm/s$. Note that both theoretical and experimental evaluations show that the energy of the plasma electrons is greater than 1 MeV. The velocity of the electrons will be $v \geq \sqrt{3} \cdot c/2$. Therefore, in order to agree on this ballistic model of echo with the observations in the experiment, we must assume that, in general, the energy of the plasma electrons is concentrated in their transverse motion. The considered feature of the interaction of the microwave pulse with plasma is determined by the wave-particle interaction.

The second, less surprising result is the view of the instantaneous spectra of the plasma optical resonator. We must say that in the experiment, such spectra could only be obtained by using wideband oscilloscope with a bandwidth of 4 GHz. The dynamics of these instantaneous spectra can be seen in Fig. 3. Of these figures, first of all, it is seen that the instantaneous spectra have the linear character. Over time, these spectra are enhanced with lines both in the upper and in the lower frequencies.

Even after the end of the excitation pulse in the facility the generation of signals with frequencies of 0.4 and 2 GHz (see Fig. 3,e) proceeds. The amplitudes of these oscillations are comparable with the amplitude of vibration excitation.

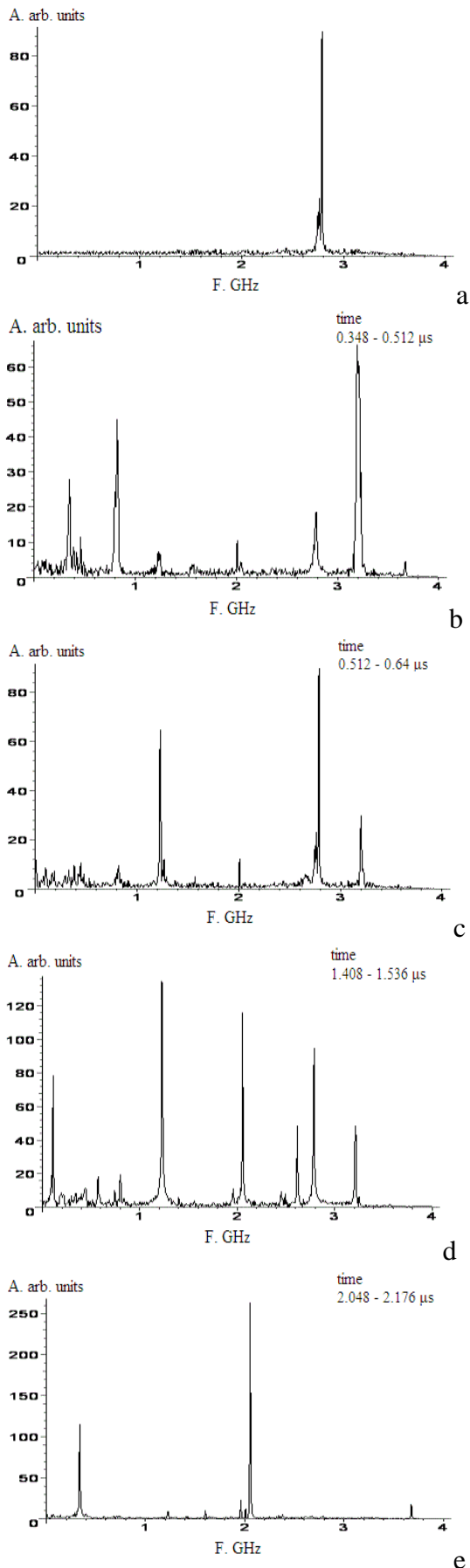


Fig. 3. In the figure (a) is presented the spectrum of the signal generated by the magnetron generators. On the other - the evolution of the signal in a resonator with a plasma over time

CONCLUSIONS

Thus, the main results of the research can be seen in the fact that the correlation processes can be stored in the dynamics of these interactions, despite the development of global stochastic instability as in the wave-particle interactions, and in wave-wave interactions. It should be noted that this feature is definitely typical only for dynamic chaos. The existence of always available fluctuations in the plasma leads to the destruction of the correlation processes. Under the conditions of these experiments the plasma was rare, so the impact of fluctuations was noticeable only after sufficiently long time. In this paper, we do not discuss this peculiarity. We note only that the instantaneous spectra are completely noise only after sufficiently long time.

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ОСОБЕННОСТИ СТОХАСТИЧЕСКОГО НАГРЕВА ПЛАЗМЫ В ПЛАЗМЕННОМ РЕЗОНАТОРЕ

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Изложены результаты изучения динамики частиц и волн при взаимодействии интенсивного электромагнитного импульса с плазмой. Показано, что в условиях, когда реализуются режимы с динамическим хаосом для взаимодействий волна-частица и волна-волна, сохраняются некоторые корреляционные процессы. Они проявляются в возникновении электромагнитных всплесков, которые возникают по истечении достаточно большого времени после окончания импульса, который действует на плазму. Кроме того, вид мгновенных спектров колебаний в плазме носит линейчатый характер.

ОСОБЛИВОСТІ СТОХАСТИЧНОГО НАГРІВУ ПЛАЗМИ В ПЛАЗМОВОМУ РЕЗОНАТОРІ

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Викладено результати вивчення динаміки часток і хвиль при взаємодії інтенсивного електромагнітного імпульсу з плазмою. Показано, що в умовах, коли реалізуються режими з динамічним хаосом для взаємодій хвиля-частка і хвиля-хвиля, зберігаються деякі кореляційні процеси. Вони проявляються в появі електромагнітних сплесків, які виникають при досягненні достатньо великого часу після закінчення імпульсу, який діє на плазму. Крім того, вигляд миттєвих спектрів коливань у плазмі носить лінійчатий характер.