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LABORATORY STUDIES OF KINETIC INSTABILITIES UNDER DOUBLE PLASMA RESONANCE CONDITION IN A MIRROR-CONFINED NONEQUILIBRIUM PLASMA

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Abstract. We study the stability of a dense nonequilibrium plasma of the electron cyclotron resonance (ECR) discharge in an open magnetic trap immediately after the end of heating. The observed instability is accompanied by pulse-periodic generation of high-power electromagnetic radiation at a frequency that is close to the frequency of the upper hybrid resonance and the double gyrofrequency of electrons and by synchronous precipitations of fast electrons from the trap. It is shown that the observed instability is connected with excitation of plasma waves under the conditions of double plasma resonance in the decaying plasma of the ECR discharge.

1. Introduction

Studies of kinetic instabilities in a nonequilibrium plasma, which is produced in an open magnetic trap by high-power electromagnetic microwave radiation under the conditions of electron cyclotron resonance, are of fundamental interest, in particular, since they allow one to model physical processes in the solar corona and the magnetospheres of the Earth and other planets. For example, plasma instabilities in the magnetic traps on the Sun are sources of high-power wideband radio emission (the so-called Type-IV radio bursts), which is interpreted as emission of plasma waves by fast electrons at the frequency of the upper hybrid resonance, followed by transformation of these waves into electromagnetic ones, e.g., as a result of scattering by thermal ions [1]. In the case of double plasma resonance, when the frequency of the upper hybrid resonance coincides with one of the electron gyrofrequency harmonics, the growth rates of instability of plasma waves increase sharply [2, 3], which leads to appearance of intense narrow bands near the harmonics of the electron gyrofrequency in the radio emission spectrum (the so-called zebra structure). It should be noted that manifestations of the double plasma resonance effect in astrophysical plasmas are not rare. Suffice it to say that the zebra structure is observed not only in the radio emission of solar bursts, but also in the Jovian decameter radio emission [4], in the radio emission of the Earth's magnetosphere [5], and even in the radio emission of pulsars [6]. Therefore, confirmation of the double plasma resonance effect in a laboratory plasma experiment seems to be a fairly important problem.

Under laboratory conditions, the cyclotron resonance heating of electrons allows one to create a nonequilibrium two-component plasma with a dense, relatively cold (background) fraction with isotropic velocity distribution of particles and a less dense, high-energy fraction of nonequilibrium electrons with anisotropic distribution function (and the greater energy of the motion transverse to the magnetic field than the energy of the longitudinal motion). In the nonequilibrium plasma of the ECR discharge, kinetic instabilities can develop as a result of interaction of energetic electrons with electromagnetic waves [7-13]. Specifically, in a dense plasma, when the condition $\omega_{ce} \leq \omega_{pe}$ (ω_{ce} and ω_{pe} are the gyrofrequency and plasma frequency of electrons, respectively) is fulfilled, instability of plasma waves can occur at frequencies near the frequency of the upper hybrid resonance, $\omega_{\rm uh} = \sqrt{\omega_{ce}^2 + \omega_{pe}^2}$.

These instabilities of a dense nonequilibrium plasma are studied immediately after the end of ECR heating in this paper. The observed instability is accompanied by generation of high-power electromagnetic radiation at a frequency close to the upper hybrid frequency and double gyrofrequency of the electrons. We discuss the possible connection between the above-specified intense radiation and the manifestation of double plasma resonance in the decaying plasma of the ECR discharge.

2. Description of the experiment

The plasma of the ECR discharge maintained in a magnetic mirror trap was studied in the experimental setup, whose layout is shown in Fig. 1. Generation and heating of the plasma under conditions of electron cyclotron resonance are maintained by gyrotron radiation with an operating frequency of 37.5 GHz, a power of 80 kW, and a pulse duration of 1 ms. The gyrotron radiation is injected to the discharge chamber center along its axis through a Teflon window brought out of the magnetic trap and a matching system, which is located in the mirror of the magnetic trap and used also as a plasma collector. Resonance heating of the plasma is performed at the fundamental harmonic of the gyrofrequency in an open axisymmetric magnetic trap. The zone of ECR absorption is located between the mirror and the central cross section of the trap and corresponds to the magnetic-field inductance equal to 1.34 T. The axisymmetric discharge chamber 7 cm in diameter is located in the magnetic trap with a length of 20 cm and a mirror configuration of magnetic-field lines. The magnetic field is produced by pulse coils (the current pulse duration is 7 ms), which ensure a magnetic field of 4.3 T in the trap mirrors, and a mirror ratio of 5. The working gas used in the experiments is nitrogen. The background pressure of the neutral gas is 10^{-6} Torr, and the operating pressure at the moment of the discharge can increase up to 10^{-3} Torr.

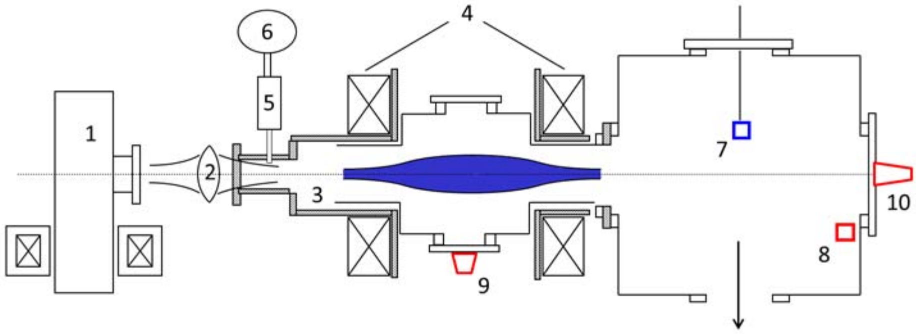

Figure 1. Layout of the experimental setup: gyrotron (*1*), dielectric lens (*2*), discharge chamber (*3*), magnetic mirror (*4*), pulse valve (*5*), receiving volume with the working gas (*6*), p-i-n-diode on a movable support (*7*), Langmuir probe (*8*), and antennas for detection of microwave radiation (*9* and *10*). The arrow shows the direction of evacuation.

In this work, the main attention is given to the studies of electromagnetic plasma activity, specifically, measurements of the spectral composition of plasma emission bursts. Additionally, a set of traditional methods [9, 11] is used to measure plasma parameters and characteristics of the energetic electrons precipitating from the trap along the magnetic field.

A set of silicon p-i-n diodes capable of detecting particles with energies from 10 to 180 keV and a single plane electric probe operating in the ion saturation current regime are used as detectors of electrons. The own electromagnetic radiation of the plasma is detected both along and across the magnetic field of the trap using receiving antennas located out of the vacuum volume. To detect plasma radiation, we used a horn antenna with a uniform passband in the range from 2 to 20 GHz. The signal from the antenna is sent to the wide-band Tektronix MSO72004C oscilloscope with the 20 GHz passband of the analog channel and a maximum time resolution of 10 ps. Alongside the horn antenna, a low-pass filter with a boundary frequency of 18.5 GHz is used to protect the channels of the oscilloscope against the high-power radiation of the gyrotron.

3. Experimental results

The use of high-power millimeter-wave radiation of the gyrotrons for heating of electrons under the cyclotron resonance conditions allows one to produce a nonequilibrium plasma with unique parameters. The plasma at the stage of a well-developed discharge is characterized by the presence of a dense cold component (the density $N_c \sim 10^{13}$ cm^{-3}, temperature $T_c \sim 300$ eV) with isotropic velocity distribution and a less dense hot electron fraction (the density $N_h \sim 10^{10}$÷10^{11} cm^{-3}, the average particle energy $T_h \sim 100$ keV) with anisotropic distribution function [11, 14]. The cold background plasma determines the dispersive properties of waves in the medium, whereas the hot electron component with a nonequilibrium velocity distribution determines the instability and generation of electromagnetic radiation under conditions where the loss-cone is empty.

The used equipment allows one to study the microwave plasma radiation at frequencies of 2 to 20 GHz with time resolution exceeding 1 ns. Fig. 2 shows the oscillogram of the electric field component of the plasma electromagnetic radiation.

Fig. 3 shows the dynamic spectrum of plasma radiation, which was obtained by using the windowed Fourier transform, and the corresponding oscillogram of the electron detector signal immediately after the microwave radiation of the gyrotron is turned off. Here and in what follows, the shades of gray in the spectrogram indicate the power spectral density on a logarithmic scale. Analysis of the experimental data allows one to determine characteristic parameters of the pulse-periodic instability regime. Radiation bursts occur at a frequency near $2f_{ce0}$, where $f_{ce0} = \omega_{ce0}/(2\pi)$ is the electron gyrofrequency at the center of the magnetic trap, duration of flares and synchronous bursts of the current of the electrons precipitating from the trap is equal to about 50 ns, and the period of their repetition is about 200 ns. It is important to note here that the upper-hybrid radiation is observed at the moment, when the frequency f_{uh} of the upper hybrid resonance becomes equal to the second harmonic of the electron gyrofrequency $2f_{ce0}$ (see Fig. 3). This is an experimental proof of the double plasma resonance effect.

Series of quasiperiodic bursts can consist of up to a hundred pulses. An example of such a series is shown in Fig. 4 and, with a better time resolution, in Fig. 5. A few of such periodical groups can follow each other at an interval of approximately 50 μs.

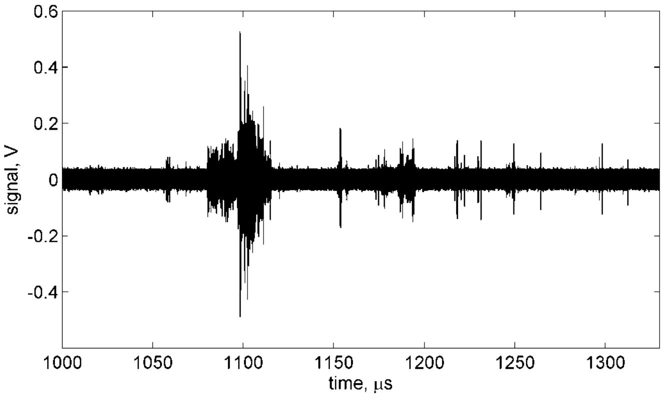

Figure 2. Oscillogram of the electric field of the detected electromagnetic wave. Here and in what follows, time is counted from the starting moment of the ECR heating, which is turned off after 1 ms.

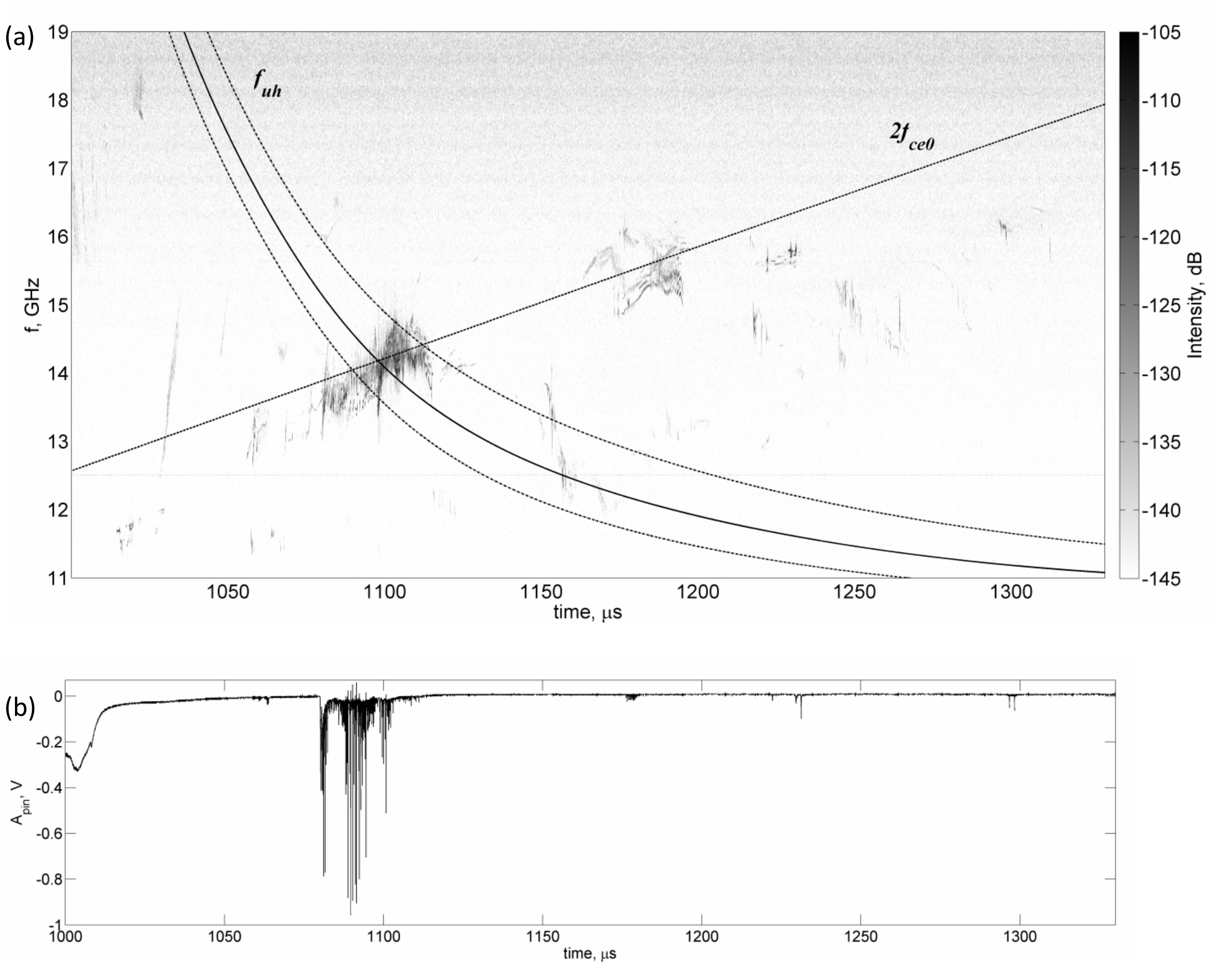

Figure 3. Panel ***a***: Dynamic spectrum of the oscillogram of the electric field shown in Fig. 2. The dashed line shows the time variation of the frequency $2f_{ce0}$, where f_{ce0} is the electron gyrofrequency at the center of the magnetic trap. The solid line shows the variation of the upper-hybrid resonance frequency f_{uh} during plasma decay. The dash-and-dot lines show the spread in determination of the frequency f_{uh} allowing for the accuracy of measuring the temperature of the background plasma (about 30%). Panel ***b***: current of the energetic electrons precipitating from the trap.

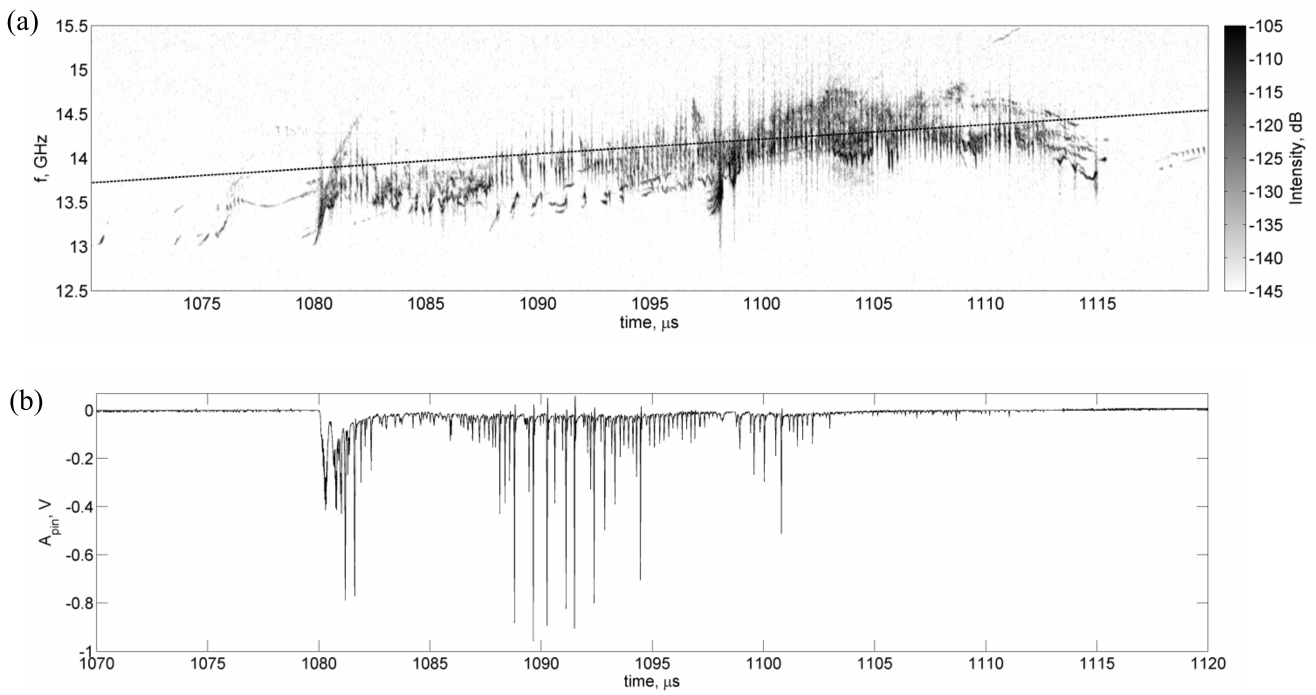

Figure 4. Fragment of Fig. 3 with a higher time resolution: a series of quasiperiodic bursts of plasma emission (***a***) and synchronous precipitations of energetic electrons from the trap (***b***).

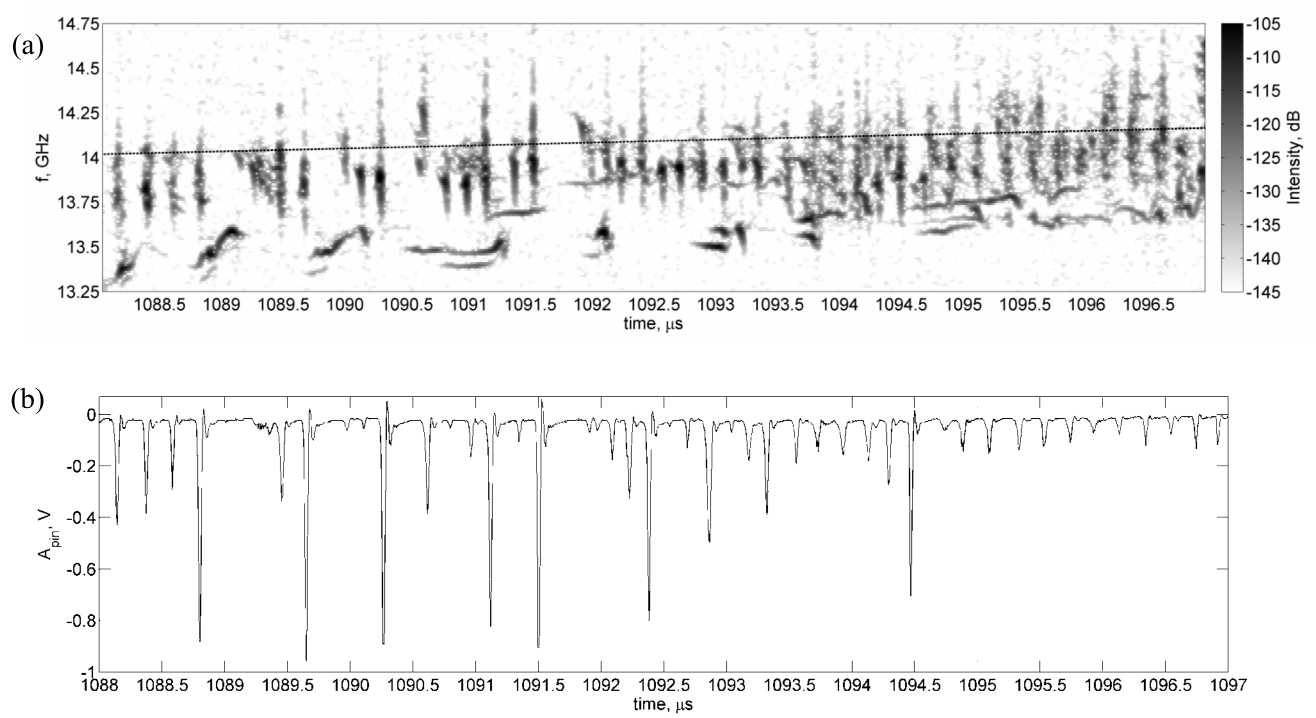

Figure 5. Fragment of Fig. 4 with a higher time resolution: a series of quasiperiodic bursts of plasma emission (***a***) and synchronous precipitations of energetic electrons from the trap (***b***).

4. Discussion

In this section, we will discuss the possible origin of the observed high-frequency plasma radiation. Consider conditions in the decaying plasma after the ECR heating at which this radiation is observed. The dynamics of the density and temperature of the plasma after the end of ECR heating was calculated within the framework of the approach based on the balance equations for the different plasma components density and its energy content, which were averaged over the trap volume [11, 15]. The corresponding plots of variations in the density and temperature of the background plasma electrons are shown in Fig. 6. One can see in the plots that when high-frequency electromagnetic radiation appears (at the time moment t = 1100 μs), the plasma density is equal to 2×10^{12} cm^{-3}. Under these conditions, the plasma frequency exceeds the electron gyrofrequency at the center of the trap ($\omega_{pe} > \omega_{ce0}$); therefore, the whistler waves at frequencies below ω_{ce0} and plasma waves at the upper hybrid frequency have the largest growth rates [16].

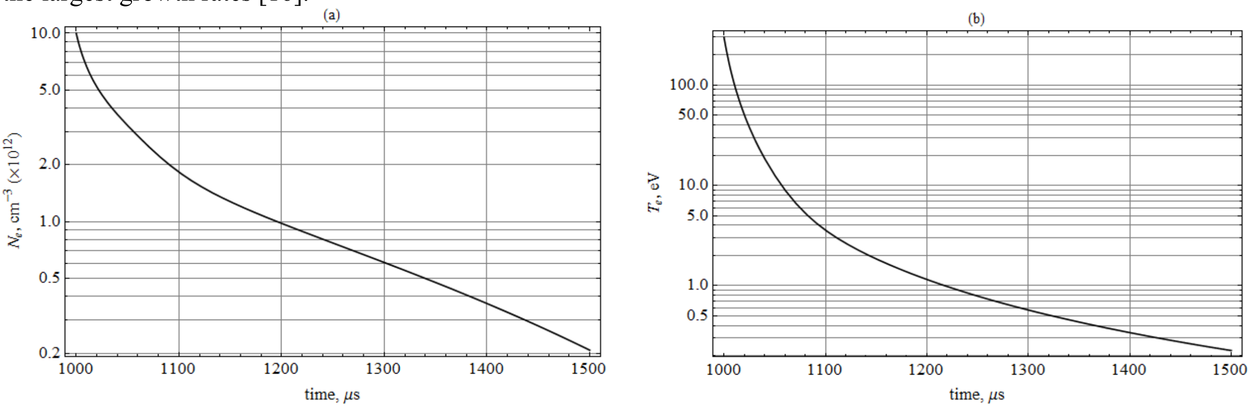

Figure 6. Calculation of the plasma decay after switching-off the ECR heating based on the balance equations for the densities of neutral and charged particles and the stored energy, which are averaged over the trap volume (in greater detail, see [15]): variation in the density N_c (***a***) and temperature T_c (***b***) of the background plasma electrons. The calculation is performed for the initial parameters $N_{c0} = 10^{13}$ cm^{-3}, T_{c0} = 300 eV.

Analysis shows that in the experiment discussed here, the unstable waves are mainly the plasma waves at the upper hybrid frequency, whose growth rates exceed those of other unstable modes by several orders of magnitude. Indeed, since the frequency of plasma waves is close to the second harmonic of electron gyrofrequency for the high-frequency component of the radiation, whose spectrum is shown in Fig. 4*a*, one can assume that at a certain stage of the plasma decay, the condition of double plasma resonance is fulfilled [17]:

$$\omega \approx \sqrt{\omega_{ce}^2 + \omega_{pe}^2 + 3k_\perp^2 \upsilon_{T_e}^2} \approx 2\omega_{ce} \quad (1)$$

where $k_\perp$ is the component of the wave vector being transverse to the magnetic field **B**, and υ_{T_e} is the thermal velocity of electrons.

The fulfilment of condition (1) leads to an increase in the growth rates of plasma waves and, consequently, an increase in the energy density of these waves and the intensity of the observed radio emission. The latter occurs as a result of transformation of plasma waves to electromagnetic waves, e.g., as a result of scattering by thermal ions. Condition (1) will be fulfilled in those regions of the trap where the relation

$$\omega_{pe} \approx \sqrt{3}\omega_{ce} \quad (2)$$

is valid for the plasma frequency and the gyrofrequency.

When condition (1) is fulfilled, the growth rate of the plasma wave is equal, in order of magnitude, to [2]

$$\Gamma \approx (0.1 \div 1)\frac{N_h}{N_c}\omega_{ce}. \quad (3)$$

The growth rate is maximum for the waves propagating across the magnetic field. The wave vector of unstable plasma waves is determined by the characteristic velocity of nonthermal resonance electrons υ_h and is of the order of $k_\perp \approx \omega/\upsilon_h$. The group velocity of plasma waves is equal to

$$\upsilon_{gr} \approx \frac{3k_\perp \upsilon_{T_e}^2}{\omega} \approx \frac{3\upsilon_{T_e}^2}{\upsilon_h} \quad (4)$$

and the spatial amplification coefficient of plasma waves

$$\mu = \frac{\Gamma}{\upsilon_{gr}} \approx (0.1 \div 1)\frac{N_h}{N_c}\frac{\omega_{ce}\upsilon_h}{3\upsilon_{T_e}^2} \quad (5)$$

in this case is equal to approximately $\mu \approx 1.5\times(10^3 \div 10^4)$ cm^{-1}.

If one assumes that the instability band width $\Delta\omega$ is equal to approximately $\Delta\omega \approx 0.1\omega$ [17], when the double plasma resonance is realized, then the integral gain for the plasma waves propagating tangentially to the magnetic-field isosurfaces can reach $3\times(10^3\div10^4)$ at the plasma volume radius $R_\perp$ = 3.5 cm. This means that nonlinear effects can affect the dynamics of plasma waves significantly. Specifically, the pulse regime of plasma wave generation can occur when the processes of wave excitation and stimulated wave scattering compete. Stimulated scattering leads to the exit of the growing packet of plasma waves from the resonance angle interval to the attenuation regime, which results in a breakdown of the instability. In the simplest case, this regime is described by the Lotka–Volterra system of equations [18]:

$$\frac{\mathrm{d}w}{\mathrm{d}t} = \Gamma w - \xi w w^*, \quad \frac{\mathrm{d}w^*}{\mathrm{d}t} = \xi w w^* - \nu w^*. \tag{6}$$

Here, w and w^* are the amplitudes of plasma turbulence in the intervals of the angles corresponding to the instability and attenuation, Γ is the instability growth rate, ξ is the coefficient of stimulated scattering of plasma waves, and ν is the damping rate of plasma waves in the nonresonance angle region. Equations (6) describe periodical solutions which correspond to closed trajectories in the phase plane (w, w^*) around a critical point with the coordinates $w_0 = \nu/\xi$ and $w_0^* = \Gamma/\xi$ (the center-type equilibrium).

If the modulation in the plasma wave energy density is weak ($|w - w_0| << w_0, |w^* - w_0^*| << w_0^*$), then the oscillation period is determined by the formula

$$T = \frac{2\pi}{\sqrt{\Gamma\nu}}. \tag{7}$$

In the case of a deep modulation $\left(|w - w_0| \approx w_0, |w^* - w_0^*| \approx w_0^*\right)$ the period of oscillations is

$$T \approx \frac{1}{\nu}\ln\left(\frac{w}{N_c T_c} N_c D_e^3\right) \approx \frac{15}{\nu}, \tag{8}$$

where D_e is the Debye radius. Based on Eq. (8) for the observed oscillations period T = 200 ns, one can estimate the damping rate of plasma waves in the nonresonance angle region: $\nu \approx 7.5\times10^7\ \mathrm{s}^{-1}$. This decrement estimate exceeds the effective frequency of electron-ion collissions $\nu_{ei} \approx 6\times10^6\ \mathrm{s}^{-1}$ at the plasma density $N_c \approx 2\times10^{12}\ \mathrm{cm}^{-3}$ and the background plasma electron temperature $T_c \approx 5$ eV, which correspond to the moment of generation of intense high-frequency radiation. On the other hand, the damping rate of plasma waves in the nonresonance plasma angle region turns to be approximately equal to the instability growth rates, which can be connected with attenuation of plasma waves at the same fast electrons that generate plasma waves in the resonance angle interval. In this case, periodic ejections of fast electrons from the trap, which coincide in time with the increase in the intensity of plasma waves, are connected with generation of plasma waves on the normal Doppler effect, which results in fast electrons' losing part of the energy of their motion across the magnetic field. As a result, generation of plasma waves leads to electrons entering the loss-cone and precipitating further out of the magnetic trap.

Another reason for the modulation in the observed radiation can be fast magnetosonic plasma oscillations in the trap. The period of such oscillations [19],

$$T_{FMS} \approx 2.6\frac{R_\perp}{\sqrt{\upsilon_A^2 + c_S^2}} \approx 90\ ns \tag{9}$$

at $R_\perp \approx 3.5$ cm, the Alfven velocity $v_A \approx 10^8$ cm/s, and the ion-acoustic velocity $v_S \approx 6\times10^5$ cm/s, which is approximately twice as low as the observed period. This fact can be connected with that Eq. (9) is obtained for an infinite plasma cylinder with no allowance for the actual geometry of the trap. In the case of fast magnetosonic oscillations, periodic precipitations of fast electrons are explained by periodic changes in the mirror ratio of the trap. In our case, the characteristic attenuation time of fast magnetosonic oscillations is determined by viscosity (see review work [20]) and amounts to about 100 μs, i.e., the order of magnitude of the high-frequency radiation intensity. This means that one cannot exclude the modulation of the plasma radiation by fast magnetosonic oscillations.

5. Conclusions

Thus, we can assume that the high-power quasiperiodic bursts of electromagnetic radiation, which are observed in the experiment after the plasma heating stage, are connected with the phenomenon of double plasma resonance. In contrast with space plasma, where double plasma resonance is observed in spatially inhomogeneous plasma at several frequencies (zebra structure), the double plasma resonance occurs in the laboratory plasma at a certain time moment in the process of plasma decay, when the decreasing frequency of the upper hybrid resonance coincides with the harmonic of the electron gyrofrequency. In this case, the growth rate of plasma waves at the frequency of the upper hybrid resonance increases by approximately an order of magnitude as compared with the case of no resonance. As a result, the intensity of radio emission from the trap increases significantly. The duration of high-frequency radiation in this experiment is as short as 30 μs only. During this time, the harmonic of the electron gyrofrequency changes by approximately 0.5 GHz, i.e., by the observed width of the radiation band, and the conditions of double plasma resonance stop being fulfilled. In this case, the pulse regime of generation of plasma waves and synchronous pulsing precipitations of fast electrons from the trap can be connected with either the competition of the instability and stimulated scattering in the process of generation of plasma waves, or the excitation of fast magnetosonic oscillations of the plasma in the magnetic trap. Since rather high amplification coefficients of plasma waves are realized under the conditions of the experiment, the first reason for occurrence of the pulsations seems to be more probable.

The mechanism of double plasma resonance is applied to explain many phenomena in astrophysics. Therefore, laboratory confirmation of this mechanism and identification of its new features, specifically, the pulse regime of generation, are of great importance for future studies of different astrophysical objects.

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