FEATURES OF BEHAVIOR OF ELECTRONS OF PLASMA IN OPEN TRAP IN CONDITION OF TRANSVERSE INPUT OF POWERFUL MICROWAVE PULSES AT ECR

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It has been experimentally shown that the effect of oscillations of large amplitude on the frequency of electron cyclotron resonance on a plasma held by a magnetic trap leads to an effective acceleration of the plasma electrons and the formation of directed electron fluxes, which in turn stimulate repeated microwave oscillations. A consequence of such a process is the appearance of alternating pulses of microwave oscillations in time.

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INTRODUCTION

As was shown in [1 - 3], when a pulse of oscillation at a frequency of electron cyclotron resonance of a large power level (tens of kV / cm) is exceeded by a certain threshold value when a plasma pulse is kept by an open magnetic trap, the appearance of a sequence of pulses of microwave oscillations is recorded. Electrons with energies of tens to hundreds of keV are detected in the plasma, the plasma density increases by two or three orders of magnitude (up to 10^{13} cm^{-3}) and the appearance of high-energy ion fluxes.

In this paper we present the results of studies that indicate the large role of electron fluxes in the nonlinear interaction of microwave waves of large amplitude at the electron-cyclotron frequency with plasma in cascade excitation of high-frequency oscillations in time.

EXPERIMENTAL SETUP

Experimental studies were performed on a facility [3], the scheme of which is shown in Fig. 1.

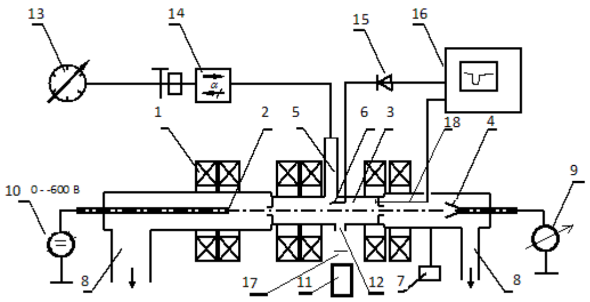

Fig. 1. The scheme of the experimental setup. 1 – magnetic field coils; 2 – electron gun; 3 – microwave cavity chamber; 4 – collector; 5 – microwave injection into the resonator; 6 – loop probe; 7 – gas inlet system; 8 – pump-out pumps of the installation; 9 – meter of collector current; 10 – power supply of the electron gun; 11 – X-ray sensor; 12 – vacuum window; 13 – magnetron; 14 – microwave valve; 15 – detector head; 16 – an oscilloscope; 17 – lead shield; 18 – current probe on the piston

The main element of the installation is a cylindrical resonator made of a copper pipe with an internal diameter of 16 cm and a length of 100 cm, which could be excited on H modes of the type. The resonator was placed coaxially with the axis of the magnetic trap. The central part of the resonator along the length, as well as the waveguide, along which the microwave signal power was applied, were located in the region of the minimum value of the magnetic field induction. The mirror ratio of the trap changed to 1.5. In this case, the minimum value of the magnetic field induction at which the electron-cyclotron resonance at the oscillation frequency of the magnetron generator of 2.77 GHz was performed was ≈ 0.1 T.

The length of the homogeneous part of the magnetic field of the trap in the resonator could vary from 25 to 100 cm. The power of the magnetron generator was regulated in the interval 0.1…1 MW in a pulse with a duration of 1.8 μs. The oscillations were fed into the resonator along a rectangular waveguide with a cross section of 72×34 mm. The narrow wall of the waveguide was located along the axis of the resonator.

By moving the resonator piston, the system was adjusted to maximize the transfer of energy from the magnetron to the resonator.

Previously, a plasma in a resonator with a density of $10^{9}…10^{10}$ cm^{-3} was produced by an electron beam with an energy of 600 eV and a current of 60…100 mA due to a beam-plasma discharge. The pressure in the resonator varied within $10^{-3}…10^{-6}$ Torr. Argon was used as working gas.

A Langmuir probe was used to measure the density, temperature, and potential of the plasma. The probe was located in the central part of the resonator and could move along the radius.

The intensity of X-ray radiation from the plasma was recorded by a sensor consisting of a NaJ scintillator with a photomultiplier FEU-36. The sensor was located in the central part of the resonator at a distance of 50 cm from the vacuum window from the lavsan film.

In addition, in the experiment, a mobile probe was used in the form of a lead ball with a diameter of 5 mm fixed on a thin dielectric rod. By measuring the intensity of X-ray radiation generated by deceleration of accelerated electrons on its surface, it was possible to establish their spatial distribution in a magnetic trap.

EXPERIMENTAL RESULTS

In general, the results of the studies are reflected in Figs. 2-6.

In Fig. 2 shows the correlation of the signals of the amplitudes of the microwave oscillations in the trap and the light radiation from the plasma when oscillations are introduced into the resonator from the magnetron generator and with a repeated pulse of the microwave oscillations.

In Fig. 3 shows the intensities of the integrated light radiation from the central part of the trap and the X-ray radiation caused by the deceleration of accelerated electrons on the target in the form of a lead ball at the time until the appearance of a repeated burst-the pulse of microwave oscillations.

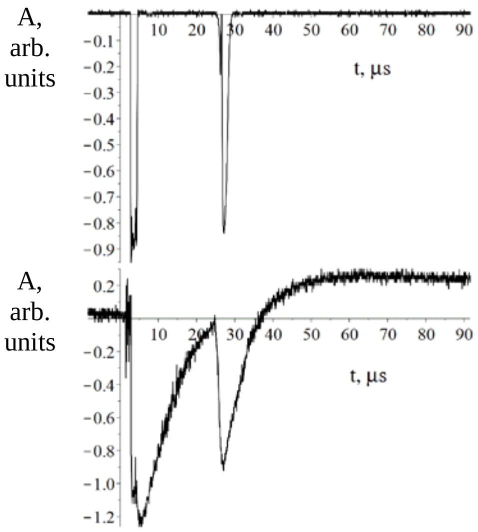

Fig. 2. Correlation of the pulses of microwave oscillations (upper oscillogram) and light radiation from the plasma (lower oscillogram)

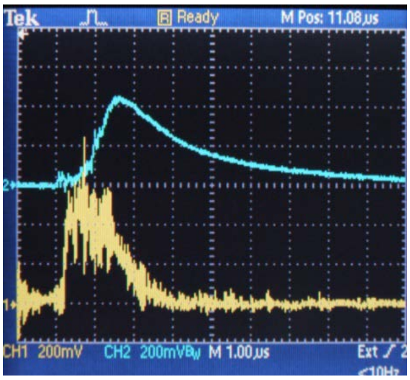

Fig. 3. Intensity of the light (upper oscillogram) and X-ray radiation (lower oscillogram) of the plasma

It can be seen from the oscillograms that light radiation appears after the excitation of microwave oscillations. In this case, its intensity between the pulses of the microwave oscillations is more than an order of magnitude smaller than in the pulse.

This indicates that in the time interval between the pulse of repeated excited oscillations, the plasma density is much smaller than the density created by microwave oscillations introduced into the trap from the magnetron. This fact is confirmed by measurements of the plasma density, using a double Langmuir probe. According to these measurements, the plasma density in the interval of the excitation pulse duration at the electron-cyclotron frequency increases from 10^{10} cm^{-3} to $10^{12}…10^{13}$ cm^{-3}. After the expiration of the pulse duration of the microwave oscillations of the magnetron, the plasma density in the trap falls practically to the level created by the beam-plasma discharge before the introduction of microwave oscillations into it.

Measurement of the power of oscillations absorbed by the plasma showed that under the conditions of electron-cyclotron resonance, it is 80…90% of the input from the magnetron generator. Measurement of the same power between pulses using calibrated loop antennas has shown that its value does not exceed 10…20% of the input. Those. even at a generator power of 300 kW, the power between pulses should be 27…54 kW. This power should be sufficient to carry out additional ionization of the residual gas at a pressure of $5{\cdot}10^{4}$ Torr.

This indicates that excitation of microwave oscillations generates a process that ensures an anomalously high diffusion of the plasma.

It can be assumed that the appearance of a repeated pulse of a dense plasma is due to the excitation of high-power microwave oscillations by electron fluxes held for a long time by the trap, which are formed as a result of acceleration by fields previously excited by microwave oscillations.

One of the corroborations of this is the correlation of X-ray radiation from a lead ball placed in the plasma and current to a probe covered by an aluminum foil 15 μm thick, located at a distance of 100 mm from the axis of the trap, as well as a pulse of generated microwave oscillations.

The second factor can be the electron distribution function obtained in experiments on the change in the intensity of X-ray radiation produced on a target placed in a plasma [8] and the weakening of the electron flux as it passes through a set of foils, by the method described in [2].

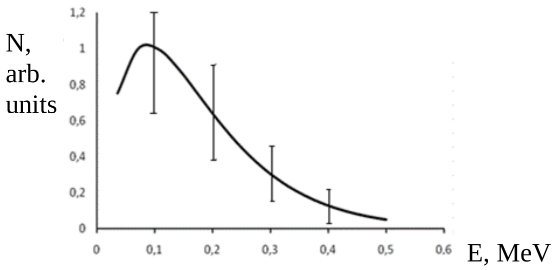

Fig. 4. Energy spectrum of electrons at a time 20 μs from the start of the microwave excitation pulse

In Fig. 4 shows the electron distribution function in 20 μs after the onset of the microwave pulse introduced into the plasma from the magnetron generator (see Fig. 2). As can be seen from the graph in the figure, the excitation of microwave oscillations is accomplished by a flow of electrons with energies from 50 to 500 keV. The maximum energy of the electron flux lies in the region of 100 keV.

The oscillations in the plasma excited by the magnetron belong to the H type. The electrons accelerated by the fields of these oscillations have a large perpendicular velocity component relative to the lines of force in the magnetic trap. This ensures their retention in the magnetic trap. If we assume, that one of the mechanisms described in Refs. [6, 7] is based on the excitation of microwave oscillation mechanisms, then the excitation of oscillations at the frequencies of the electron-cyclotron resonance should be due to the perpendicular component of the electron-beam energy. Those when excitation of electromagnetic oscillations the electrons should decrease the perpendicular component of the velocity. This should lead to a decrease in the ratio of the transverse component of the electron velocity to the longitudinal component and should allow some of the electrons to leave the trap in the loss cone, determined by the mirror ratio of the magnetic fields of the trap [5].

Indeed, as measurements of the spatial distribution of accelerated electrons with a lead ball showed, with a 300 kW power input from the magnetron, their maximum concentration is located at a distance of 4 cm from the axis of the trap. With repeated excitation of oscillations, an electron flux appears along the axis of the trap at the same distance from the axis (see Fig. 5).

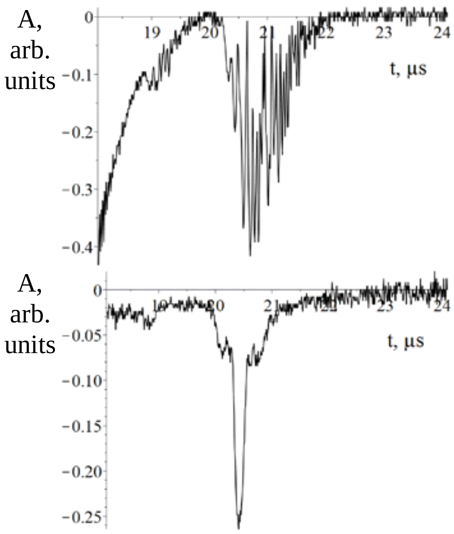

Fig. 5. Correlation of the repeated microwave pulse (upper oscillogram) and the flux of electrons leaving the trap in the loss cone (lower oscillogram)

We can assume that the appearance of repeated pulses is due to microwave oscillations by the excited counterpropagating electron beams reflected from the plugs of the magnetic trap having the same azimuthal velocity component along the trap axis. The magnitude of the power of the excited oscillations in the plasma determines the spread of the electron energy, and at the same time, the Larmor radius. The counter motion of the electron flow determines their spatial grouping along the radius of the trap. If the positions of the electron clusters coincide with the negative phase of the azimuthal component of the field of the transverse vibration mode of the resonator, their amplification occurs due to the electron energy. This adjustment of the resonance between the velocity of a bunch of electrons with an intrinsic mode of oscillations in a plasma can be facilitated by a change in its density over time [7].

The existence of a change in the plasma density with time can be indicated by the light emission recorded experimentally in time from the plasma (see Fig. 2). A confirmation of the assumed scheme of excitation of repeated pulses of microwave oscillations can also be the experimental fact that in the absence of one of the plugs, repeated pulses are not observed. With a constant value of the input power from the generator, a change in the distance between the plugs of the trap leads to a change in the synchronous phase of the placement of a bunch of electrons in the wave field.

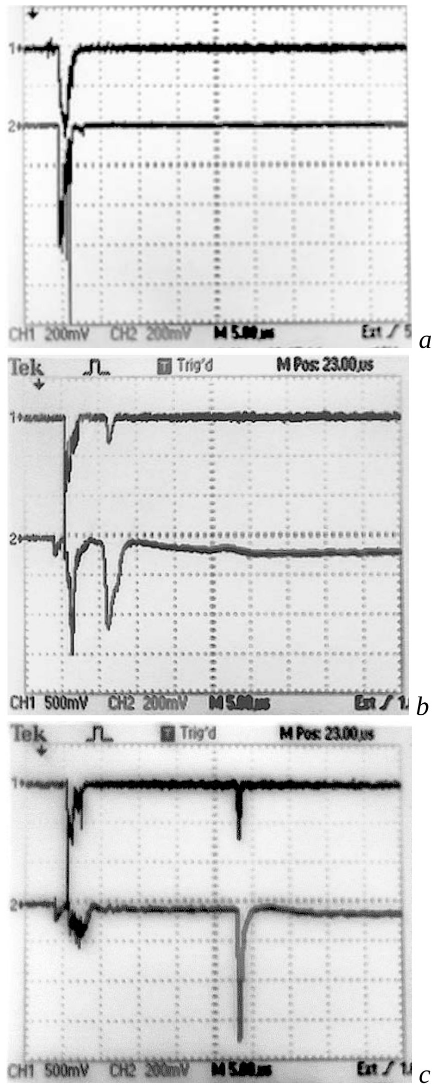

Fig. 6. Amplitudes of microwave oscillations from the loop antenna (upper oscillograms) and X-ray intensity (lower oscillograms):
a) homogeneous magnetic field (no magnetic plugs);
b) trap length 87 cm; c) trap length 95 cm

A consequence of this is a change in the observed time interval between the excited pulses of the microwave oscillations (see Fig. 6).

CONCLUSIONS

Thus, in general, the conducted experimental studies provide a qualitative picture of the interaction of intense electromagnetic radiation with the plasma of the magnetic trap in which the interaction of the electron fluxes generated by the field of a large amplitude wave at the frequency of the ECR with the plasma plays an important role.

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ОСОБЕННОСТИ ПОВЕДЕНИЯ ЭЛЕКТРОНОВ ПЛАЗМЫ В ОТКРЫТОЙ ЛОВУШКЕ ПРИ ПОПЕРЕЧНОМ ВВОДЕ МОЩНЫХ СВЧ-ИМПУЛЬСОВ НА ЧАСТОТЕ ЭЦР

А.Н. Антонов, В.С. Антипов, Е.А. Корнилов, В.А. Винокуров

Экспериментально показано, что воздействие колебаний большой амплитуды на частоте электронно-циклотронного резонанса на плазму, удерживаемою магнитной ловушкой, приводит к эффективному ускорению электронов плазмы и формированию направленных потоков электронов, которые, в свою очередь, возбуждают повторные СВЧ-колебания. Следствием такого процесса является появление чередующихся во времени импульсов СВЧ-колебаний.

ОСОБЛИВОСТІ ПОВЕДІНКИ ЕЛЕКТРОНІВ ПЛАЗМИ У ВІДКРИТІЙ ПАСТЦІ ПРИ ПОПЕРЕЧНОМУ ВВЕДЕННІ ПОТУЖНИХ НВЧ-ІМПУЛЬСІВ НА ЧАСТОТІ ЕЦР

О.М. Антонов, В.С. Антіпов, Є.О. Корнілов, В.О. Винокуров

Експериментально показано, що вплив коливань великої амплітуди на частоті електронно-циклотронного резонансу на плазму, що утримується магнітною пасткою, призводить до ефективного прискорення електронів плазми і формування направлених потоків електронів, які, в свою чергу, збуджують повторні НВЧ-коливання. Наслідком такого процесу є поява імпульсів НВЧ-коливань, які чергуються в часі.