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EXCITATION OF ION CYCLOTRON WAVES IN A PLASMA IN A TOROIDAL MAGNETIC TRAP

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The effectiveness of ion-cyclotron heating of plasma was demonstrated experimentally in [1 - 4]. However, the waves were excited in these experiments in mirror-configuration magnetic traps, in setups with a straight geometry [1 - 2] or else on the linear section of closed magnetic traps [3, 4]. It was noted in [4] that, owing to the presence of a "magnetic boundary" there takes place during the heating pulse a loss of plasma density under the exciting loop, as a result of which the conditions for the resonance in the coupling between the plasma and the loop are violated and the heating efficiency greatly decreases. In attempts to ensure gradual thermalization of the wave energy along the entire stellarator axis, it was observed that the wave excited by the spatially-periodic loop does not propagate along the curvilinear sections. In addition, the presence of a linear section distorts the geometry of the magnetic field of the trap, and the ceramic section makes the distance between the loop and the plasma larger, decreasing their mutual coupling.

We report in this paper the results of an investigation of wave excitation in a plasma situated in a toroidal magnetic field (without a linear section) with the aid of exciting elements (EE) introduced inside the chamber and located near the plasma boundary. The solution of this problem allows us to approach a study of high-frequency methods for heating a dense plasma in a

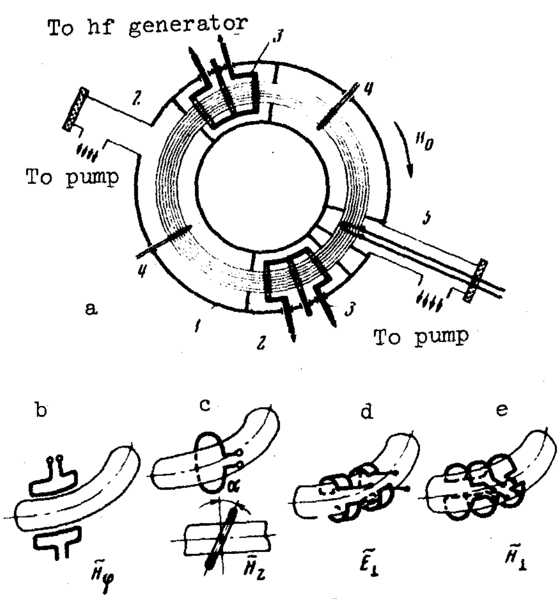

Fig. 1

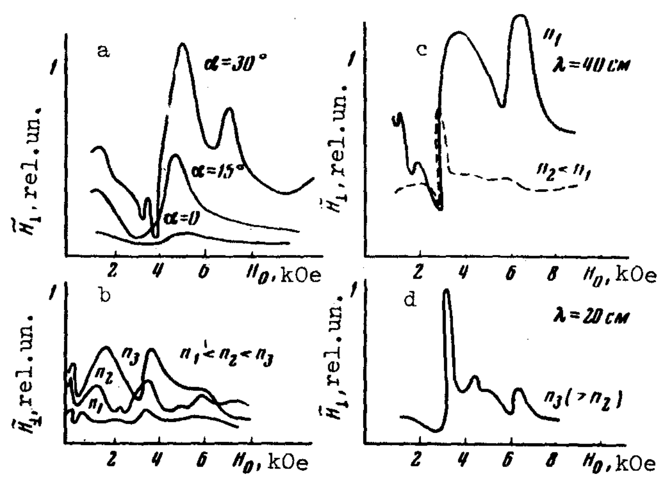

Fig. 2

Fig. 1. a) Diagram of setup: 1 - vacuum chamber, 2 - diaphragm, 3 - exciting element, 4 - high-frequency magnetic probe, 5 - cathode of electron gun. b - d) Exciting elements.

Fig. 2. Field amplitude ($H_\perp$) of wave in plasma vs. intensity of external magnetic field (H_0): excitation with loop (Fig. 1b), frequency 4.8 MHz; b, c, d - excitation with EE of Fig. 1d, f = 4.2 MHz.

system with a toroidal field, particularly by means of stochastic external irregular fields.

The experiments were performed with the "Omega" apparatus (Fig. 1a). The toroidal copper vacuum chamber (D = 800 mm, d = 300 mm) was placed in a stationary magnetic field whose intensity could be continuously regulated from 0 to 10 kOe. Copper diaphragms with inside diameter 80 mm were used to limit the discharge diameter and decrease the bombardment of the chamber wall by plasma particles. A plasma of density $10^{12} - 10^{14}$ cm^{-3} was produced by an electron beam. The plasma parameter remained practically unchanged when the magnetic field was varied in the range from 2 to 10 kOe. The intensity of the magnetic field of the wave in the plasma was measured with probes having few turns and a diameter of 3 mm, introduced into the chamber in quartz tubes. In the lower part of Fig. 1 are shown some of the investigated EE, which excited in the plasma axially-symmetrical (Fig. 1b, c) and axially-asymmetrical (Figs. 1d, e) components of the high-frequency field.

No wave fields could be observed in the plasma when fields from azimuthally-symmetrical EE were applied to it. However, when the plane of the EE loop was inclined (Fig. 1c) to the plasma axis at an angle α, excitation of ion-cyclotron and fast magnetosonic waves was observed. Figure 2a shows plots of the amplitude $\tilde{H}$ in the plasma against the intensity of the external magnetic field H_0 for different angles α, and Fig. 2b shows the same for different plasma densities. We see that the field intensity of the wave increases with increasing angle or density.

Investigations of the field structure with two probes moved along the radius of the chamber in mutually perpendicular directions have shown that the component $\tilde{H}_z$ in the excited plasma is small compared with $\tilde{H}_\perp$. The presence of a maximum of the field $\tilde{H}_\perp$ in the center of the chamber corresponds, in accordance with the theory, to an axially-asymmetrical wave with one variation in the azimuth. It was observed that the direction of the field $\tilde{H}_\perp$ makes an angle of about 45° with the axis of the torus. A study of the picture of the wave field has made it possible to select an EE construction (Fig. 1e) producing a transverse ($\tilde{H}_\perp$) high-frequency field in the plasma at an angle 45° to the torus axis. This ensured good coupling with the plasma and made it possible to increase the effectiveness of wave excitation. By externally switching the EE (Fig. 1b) it was possible to produce a vacuum field structure with λ = 20 cm (two half-waves) and λ = 40 cm (one half-wave), and variation of the plasma density makes it possible to make the wavelength in the plasma equal to the wavelength of the EE, i.e., to ensure resonant coupling, as is clearly illustrated in Figs. 2c and 2d. Figure 2b shows that such an EE excites effectively not only ion-cyclotron waves (in fields $H_0 > H_{ic}$), but also fast magnetosonic waves ($H_0 < H_{iv}$).

The described experiments were performed at low levels of power supplied to the plasma (HF current in EE about 300 A). Further investigations will be aimed at increasing the level of the power supplied to the wave with subsequent randomization of the energy of the particles in the wave.

Thus, the experiments have demonstrated the possibility of effectively exciting axially asymmetrical ion-cyclotron waves and fast magnetosonic waves in a plasma of toroidal geometry, an excitation needed to realize high-frequency heating of a dense plasma in closed magnetic traps.

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OSCILLATIONS OF EXCITATION FUNCTION OF HELIUM RESONANCE LINE AND INTERFERENCE OF TWO VACANT STATES IN COLLISIONS OF Na^+ IONS WITH HELIUM

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One of the authors has previously observed [1], in a study of the glow produced by the collisions $Na^+ + Ne \rightarrow Na^+ + Ne^*$, regular oscillations of the excitation function of two resonant lines of the helium atoms. At sodium ion energies from 0.2 to 11 keV, eight maxima, equidistant in the reciprocal relative-motion velocity, were observed. The observed oscillations were attributed to interference between the excitation channel and the charge-exchange channel adjacent to it in energy, both channels being coherently excited in the $Na^+ + Ne$ collisions. The interference of the states in such a case is the consequence of the additional interaction of two quasimolecular terms when the particles move apart. This interaction is the result of either intersection of the terms [2] or their very close approach [1] at a large internuclear distance. It was noted in [1] that in such a case the oscillations in the two inelastic channels in question should be in antiphase.

We report here experimental data which, in the authors' opinion, represent one more case wherein singularities, due to interference of two states when the particles move apart, have appeared in the total cross sections of two inelastic channels.

We measured the intensities Q_1 of the He I resonance line ($\lambda = 584.3$ Å) excited in the reaction

$$Na^+ + He \rightarrow Na^+ + He(2p\,^1P^0) - 21.22\ \text{eV}. \qquad (1)$$

The measurements were made in the 1 - 13 kV energy range. The experimental setup and the procedure used to investigate the spectral lines lying in the region of the vacuum ultraviolet are described in [3, 1]. The points on the figure represent the values of Q_1 in units of the reciprocal velocity of the relative motion of the colliding partners. It is seen from the figure that the positions of the three maxima on the curve are approximately equidistant, the distance between the extrema being $\Delta v^{-1} = 1.2 \times 10^{-8}$ sec/cm. The dashed curve represents Maurer's prewar results [4] on the measurement of the cross section Q_2 for the excitation of the yellow doublet of sodium Na I (5890/5896 Å) in the process of charge exchange of Na^+ ions on He atoms

$$Na^+ + He \rightarrow Na^+(3p\,^2P_{1/2,3/2}) + He^+ - 21.55\ \text{eV}. \qquad (2)$$

It should be noted that at low energies (large values of v^{-1} in the figure) the details of the relative course of the cross section Q_2 might have been omitted by Maurer, since he used a photographic registration procedure, and the measurements were made with appreciable intervals between the energy values. The relative course of the excitation function of the doublet lines can be regarded as reliably established in the region of the extrema (i.e., at Na^+ ion energies above 5 keV, $v^{-1} < 5 \times 10^{-8}$ sec/cm. The absolute values of Q_2 were obtained in [4] by comparing the summary intensity of the yellow doublet with the then-known value of the cross section for the excitation of the 5876-Å He I line by electron impact.