[6] J. Lindhard, Phys. Rev. Lett. 12, 126 (1964).

HIGH-FREQUENCY HEATING OF A PLASMA UNDER CONDITIONS OF ION-ION HYBRID RESONANCE

V.F. Tarasenko, S.S. Ovchinnikov, S.S. Kalinichenko, P.I. Kurilko, O.M. Shvets, and V.T. Tolok

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One of the main problems in controlled thermonuclear fusion is the development of methods of plasma heating in closed magnetic traps. An important role in its solution can be played by high-frequency heating methods. We have reported in [1] that the ions of a dense plasma can be heated with high efficiency in a toroidal trap by axially-asymmetrical ion-cyclotron waves which are damped in the region of an attenuated magnetic field (by a "magnetic beach").

In the present communication we report experimental results of heating of a plasma consisting of a mixture of hydrogen and deuterium ions in the "Omega" apparatus, with a toroidal magnetic field that is uniform along the axis under conditions of ion-ion hybrid resonance.

As is well known, an opacity region, in which the wave amplitude decreases exponentially, usually exists between the boundary of a radially inhomogeneous plasma and the resonance region [2]. For the waves to penetrate into the resonance region it is necessary that the dimensions of the opacity region be smaller than the length of the exciting wave. As shown by a theoretical analysis, in the general case the values of the plasma density corresponding to the zeroes (0) and poles (∞) of the function $k^2(r)$, i.e., to the points of reflection and absorption, are quantities of the same order of magnitude. Consequently, the penetration of a wave into the central region of the plasma, where it is desirable to produce resonance conditions, may be very difficult because of the presence of reflection points in the region of plasma density values that are smaller than on the axis ($n_0(r) < n_\infty$, $n_0 \sim n_\infty$). However, if the condition $B \ll 1$ ($B > 0$ are satisfied[1]), the values of n_0 and n_∞ turn out to be essentially different

$$X_\infty = -\frac{2C}{B}, \quad X_0^{\pm} = \frac{C}{\sqrt{-A}} \text{ where } X(r) \quad \frac{\omega_{pi}^2(r)}{\omega_{ci}^2},$$

$$C \equiv 1 - \frac{k_\parallel^2}{k^2}, \quad B \equiv -\frac{2\Omega_1^2}{NZ}[N(1-\Omega_2^2) \quad 2(1-\Omega_1^2)],$$

$$A \equiv -\frac{1}{N^2Z}[\Omega_1(1-\Omega_2^2)N^2 - 2\Omega_1^2(\Omega_1\Omega_2 - 1)N + \Omega_1^2(1-\Omega_1^2)],$$

$$Z \equiv (1-\Omega_1^2)(1-\Omega_2^2); \quad \Omega_{1,2} = \frac{\omega_{ci\,1,2}}{\omega}, \quad N = \frac{n_1}{n_2}$$

n is the ion concentration (the subscripts 1 and 2 pertain to deuterons and protons, respectively). As follows from (1), the reflection point shifts into the region of low plasma densities, where $\lambda\!\!\!^{-}_\perp \equiv 1/k_\perp(r) > L_\perp$ ($L_\perp$ is the dimension of the opacity region). In this case the wave energy can pass from the exciting device into the propagation region where $k_\perp^2 > 0$.

The high-frequency power was fed into the plasma with the aid of exciting devices that produce in the plasma a wavelength $\lambda_\parallel \sim 130$ cm, analogous to those

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[1] The condition $B > 0$ ensures transparency of the plasma in the region $n(r) < n_\infty$.

described in [1]. The exciting devices, which produce in the plasma a transverse high-frequency magnetic field, were placed inside the vacuum chamber. The plasma was produced by ionizing the working gases with an oscillating electron beam. The radial distribution of the plasma was approximately bell-shaped. The working frequency of the generator was f = 4.1 MHz.

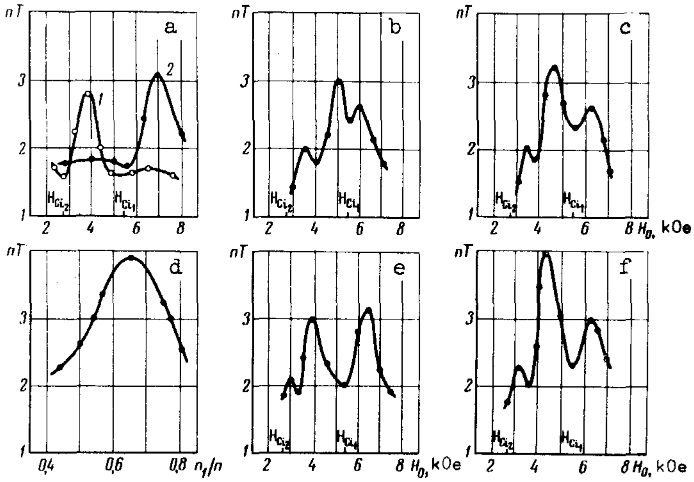

Fig. 1. Dependence of the gas-kinetic plasma pressure nT (in relative units) on the intensity of the external magnetic field H_0: a(1) - the working gas is hydrogen, a(2) - the working gas is deuterium, b - d - for a mixture of deuterium and hydrogen (b - $n_1/n = 0.53$, c - $n_1/n = 0.57$, d - $n_1/n = 0.65$, e - $n_1/n = 0.76$), f - dependence of nT on the relative deuteron concentration. (H_{ci_1} and H_{ci_2} are the cyclotron values of the magnetic field intensity for deuterons and protons, respectively).

To assess the possibility of wave excitation and plasma heating under different experimental conditions, we measured the dependences of the diamagnetic signal (nT) on the intensity of the stationary magnetic field H_0.

Figure 1a shows a plot of nT = f(H_0) for the case when the working gas was hydrogen (curve 1). The maximum of the diamagnetic signal orcurred at $H_{ci_2} < H_0 < H_{ci_1}$. It must be noted, however, that this heating is connected with absorption of the ion-cyclotron wave by protons only. For comparison, the same figure shows the analogous plot for deuterons (curve 2).

The dependence of the diamagnetic signal on the magnetic field H_0 when working with a mixture of hydrogen and deuterium ions is shown in Fig. 1b. The curve shows three maxima. The maximum in the field $H_0 > H_{ci_2}$ corresponds to heating of the protons and in the field $H_0 > H_{ci_1}$ to heating of the deuterons by the ion-cyclotron waves. At $H_{ci_2} < H_0 < H_{ci_1}$ the deuterium-hydrogen plasma ions are heated under conditions of ion-ion hybrid resonance.

The calculations have shown that at $N \sim 1$ and a wavelength $\lambda_{\parallel} \sim 130$ cm the resonant density of the plasma is $n_{\infty} \simeq 10^{14}$ cm^{-3} at a cutoff-point density $n_0 \simeq 5 \times 10^{12}$ cm^{-3}. In the experiments, the maximum value of the diamagnetic signal was observed at a plasma density on the plasma-filament axis $n \simeq 10^{14}$ cm^{-3}. The amplitude of the diamagnetic signal decreased with decreasing plasma density.

To determine the optimal conditions for heating a mixture of protons and deuterons, we measured the dependence of the diamagnetic signal on the magnetic field intensity H_0 at different relative concentrations of these ions (Figs. 1b, c, d, e). The total plasma density in these experiments was maintained constant at $n = 10^{14}$ cm^{-3}. With increasing deuteron concentrations, we observed a shift of the maximum of nT corresponding to hybrid resonance into the region of lower magnetic field intensities H_0.

The dependence of the diamagnetic signal on the relative concentration of the deuterons is shown in Fig. 1c. The maximum value of nT of the plasma was reached at a relative deuterium-ion concentration 65%.

The experiments allow us to draw the following conclusions:

1. Effective excitation of waves in a dense plasma situated in a toroidal magnetic field is possible in the region of ion-ion hybrid resonance.

2. By choosing the length of the wave excited in the plasma and the relative concentrations of the working gases it is possible to ensure penetration of waves into a dense plasma in a wide range of experimental conditions.

3. The ions of a dense three-component plasma could be heated along the entire length of the torus when resonance conditions were satisfied near the axis of the plasma filament. The gas-kinetic pressure of the plasma under the experimental conditions reached values $nT \approx 10^{16}$ eV/cm^3 at a plasma density $n \approx 10^{14}$ cm^{-3}.

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[1] S.S. Ovchinnikov, S.S. Kalinichenko, P.I. Kurilko, O.M. Shvets, and V.T. Tolok, Fourth International Conference on Plasma Physics and Controlled Thermonuclear Reactions, Madison, Wisconsin, Paper CN-28/L8, 1972.
[2] T. Stix, Theory of Plasma Waves, McGraw, 1962.

EXCITON PLASMA RESONANCE IN SEMICONDUCTORS

A.A. Rogachev and G.L. Eristavi
A.F. Ioffe Physico-technical Institute, Leningrad
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The presence of a high carrier density in a semiconductor leads to a screening of the Coulomb interaction of the carriers, which in turn causes attenuation or annihilation of the exciton absorption in the semiconductors [1 - 3]. At low densities other manifestations of the interaction between the excitons and the free-carrier plasma are possible.

We present here the results of an experimental investigation of the interaction of excitons with free carriers at densities when the exciton binding energy in the ground or excited state is higher than $\hbar\omega_p$, where ω_p is the plasma frequency. In this case the dielectric constant $\varepsilon(\omega, \vec{k})$ turns out to be smaller than the high-frequency dielectric constant of the semiconductor $\varepsilon(\infty)$ in a wide range of ω and k, so that the presence of free carriers intensifies the Coulomb interaction [4]. The interaction can be particularly intensified when $\varepsilon(\omega, \vec{k}) \to 0$, i.e., when the plasma oscillations are at resonance with certain Fourier components of the exciton wave function. Evidence of the presence of such intensification of the interaction should be an increase in the exciton absorption in the corresponding regions of the exciton spectrum when free carriers are produced in the sample.

We investigated the edge of direct absorption of germanium near $k = 0$. The absorption was measured on samples of antimony-doped n-type germanium placed in liquid helium. The free carriers were produced by pulsed breakdown of the shallow impurity centers. The experimental setup made it possible to plot the spectra of the absorption edge during the time of application of the electric-field pulses. Since the free electrons were at the extrema of the conduction band at $k = [111]$, the errors connected with the filling of the states near the edges of the bands. The absorption spectra of doped germanium at different electric field intensities are shown in the figure. The absorption near the edge