Soviet Phys. JETP 22, 1205 (1966).
[6] S. V. Krivokhizha and I. L. Fabelinskii, JETP 50, 3 (1966), Soviet Phys. JETP 23, 1 (1966).
[7] G. B. Benedek and T. Graytok, Proc. IEEE 35, 1623 (1965).
[8] L. Bergmann, Ultrasonics and their Scientific and Technical Applications, Bell, 1938.
[9] E. L. Heassel and J. Lamb, Proc. Phys. Soc. B69, 869 (1951).

# ION CYCLOTRON RESONANCE IN A DENSE PLASMA WITH HOT ELECTRONS

L. V. Dubovoi, V. D. Dyatlov, and V. P. Fedyakov
Submitted 2 August 1966
ZhETF Pis'ma 4, No. 10, 388-393, 15 November 1966

Comparison of the data obtained in [1,2] shows that the efficiency of heating of plasma ions by cyclotron resonance is greatly enhanced with increasing temperature $T_e$ of the electronic component of the plasma. In this paper we report results of an experimental investigation of the properties of a dense plasma with preheated electrons in the ion cyclotron resonance region. The experiments were made in a magnetic mirror trap. The electrons were heated by a direct turbulent discharge. The main parameters of the apparatus and the method of producing the plasma with the hot electrons were described earlier in [3]. At the instant when the heating of the electrons was terminated, and at an initial hydrogen pressure $4 \times 10^{-4}$ mm Hg, a plasma with energy density $nT_e \cong 5 \times 10^{16}$ eV/cm$^3$ ($n_e \sim 4 \times 10^{13}$ cm$^{-3}$, $T_e \sim 1$ keV) was produced in a quartz chamber 100 cm long and 10 cm in diameter, with diaphragms of 7.0 cm diameter to limit the diameter of the current pinch.

Figure 1 shows the time dependences of $nT_e$, obtained from the measurements of the diamagnetic effect in the plasma, for mirror ratios $\beta = 1.4$, 2.7, and 4.3.

The $nT_e$ decay is exponential, the kink on the obtained curves corresponds to the termination of the discharge current, and the increased rate of $nT_e$ decay when the current passes through the plasma is apparently connected with the presence of anomalous diffusion.

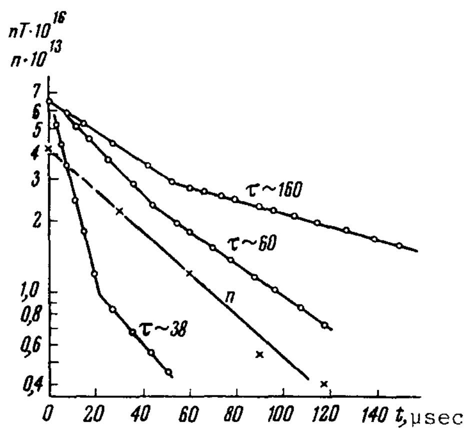


Fig. 1. Plasma decay at different trap mirror ratios: $\beta = 4.3$, $\tau = 160$ μsec; $\beta = 2.7$, $\tau = 60$ μsec; $\beta = 1.44$, $\tau = 38$ μsec.

In the first part of the investigation, the cyclotron absorption of the energy of the probing high frequency fields was used to measure the parameters of the ionic component of the plasma. The rapidly alternating field needed to excite the ion cyclotron wave was produced with the aid of four-section Stix coils [1] with a spatial period $2\lambda = 40$ cm, placed in the homogeneous part of the magnetic field $B_0$ of the trap. The coil, in turn, was an element of the tank circuit of a 200-W high-frequency oscillator operating at $f_0 = 7.12$ MHz. To increase the efficiency of wave dissipation, a "magnetic beach" [1] could be produced in the trap.

Figure 2 shows plots of the high-energy power W absorbed from the tank circuit at different values of $B_0$, taken at 30 μsec time intervals Δt starting with the instant of turning on the direct discharge. Characteristic features of the obtained curves are: the presence of a narrow absorption region at $B_c = 4.75$ kOe, corresponding to the condition of single-particle resonance for hydrogen atoms, and of absorption bands at $B > B_c$ connected with ionic cyclotron wave generation. Inasmuch as under the experimental conditions the half-width of the experimental curves at $B = B_c$ was independent of the initial density of the neutral particles and of the plasma density, it could be assumed that the plasma was collisionless, and we calculated the longitudinal component of the ion temperature from the form of the absorption curves in accord with the theory [1]. Suitable processing of the experimental absorption curves in the $B = B_c$ region shows that during the first 100 - 120 μsec of the plasma decay the value of $T_{\parallel}$ varies little and its order of magnitude is 100 eV, i.e., as assumed, $T_e > T_i$ after the completion of the turbulent heating. The position of the absorption maximum $W(B_0)$ (Fig. 2) in the region $B > B_c$, which corresponds to resonant excitation of a cyclotron wave with wavelength λ = 20 cm [1], enables us to measure the ion concentration $n_i(t)$. In Fig. 1, besides plots of $nT_e = f(t)$, we present a plot of $n_i(t)$ obtained by this method for the particular mirror ratio β = 2.2. We see that the decay constant of $nT_e$ at β = 2.7 is close to τ for $n_i(t)$ at β = 2.2. Considering that $n_e \equiv n_i$, this offers evidence in favor of the mechanism whereby the decrease of $nT_e$ with time is connected with escape of the particles from the trap while their temperatures $T_e$ remain constant.

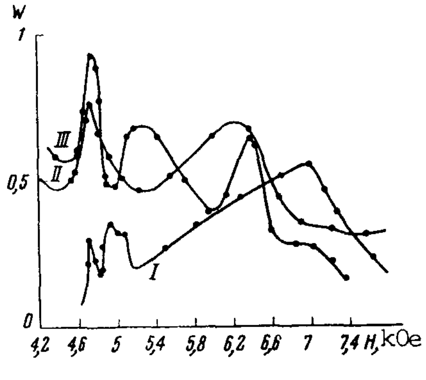


Fig. 2. High-frequency power from generator with $f_0 = 7.12$ MHz, absorbed by the plasma at different values of the magnetic field $B_0$. I) Δt = 30 μsec, II) Δt = 60 μsec, III) Δt = 90 μsec.

Mention should be made of one peculiarity of the curves of Fig. 2, in that a series of absorption maxima (curve III) is observed when $B > B_c$. This is apparently connected with the generation of higher spatial harmonics of the cyclotron wave.

In the second part of the work we attempted to heat the ions under the conditions of the experiment. The heating was with a short packet of powerful damped electromagnetic field oscillations, which generated in the plasma a rapidly dissipating cyclotron wave of large amplitude. The exciting field was produced by a shock circuit with capacitance $C_0 \sim 50{,}000$ and stored energy $Q \sim 10 - 12$ J, at a frequency 2.3 MHz. With the intrinsic Q of the circuit of the order of 50, the time necessary for complete discharge of the system was always much shorter than the decay constant τ of the plasma. With that, unlike in [1,2], the plasma heating is independent of the mechanism retaining the particles in the trap and can be investigated in pure form.

Figure 3 shows an oscillogram of the variation of the magnetic flux in the plasma, $\delta B \sim n(T_e + T_i)$, when the direct-discharge current, used to heat the electrons ($T_e > T_i$), and

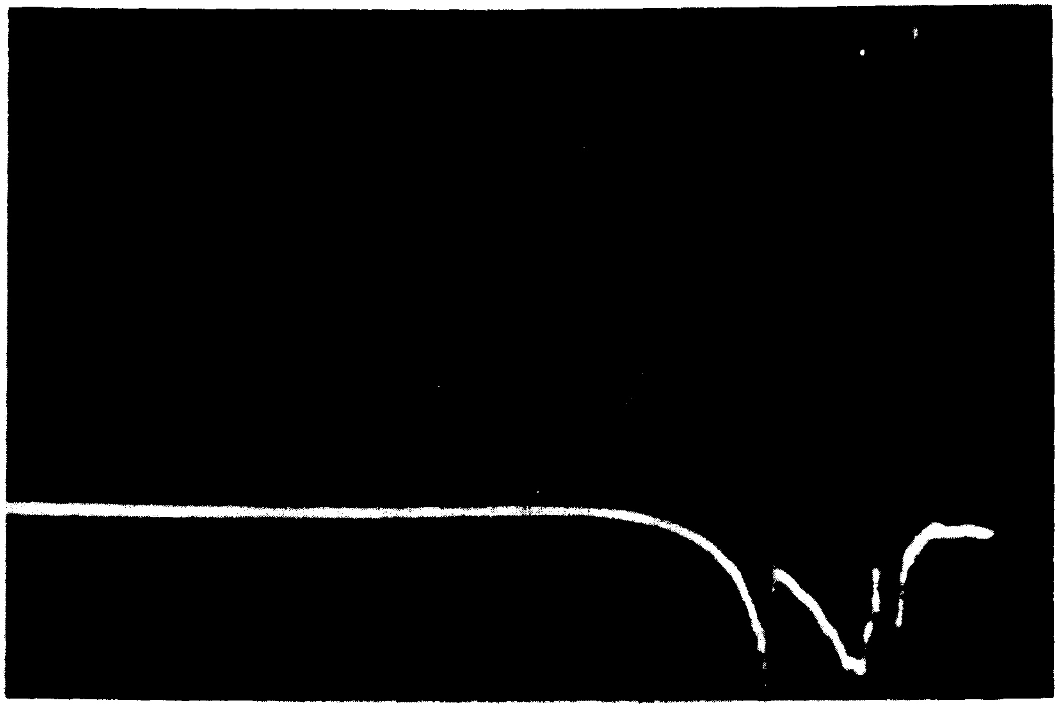

Fig. 3. Oscillograms of the diamagnetic effect in a plasma for successive operation of the direct discharge and of the shock excitation circuit.

the shock-excitation circuit for cyclotron heating of the ions are operated in succession. The circuit was operated at values of B corresponding to the generation of a cyclotron wave of maximum amplitude. In accordance with the measurements, $nT_e \sim 2 \times 10^{16}$ eV/cm$^3$, $n \sim 2 \times 10^{13}$, and $T_e \sim 1$ keV at the instant of operation of the shock-excitation circuit. At the instant when the ion heating ends, $n(T_e + T_i) \sim 4 \times 10^{16}$ eV/cm$^3$ and we can expect $T_e \sim T_i \sim 1$ keV. Actually, the experimentally obtained $\delta B_i(B)$ plot (the amplitude of the second peak of the oscillogram of Fig. 3) has a clearly pronounced resonant character, similar to the case shown in Fig. 2. It follows therefore that the amplitude of the second peak of the diamagnetic signal is connected only with ion heating. The fraction of the energy transferred to the plasma, determined from measurements of the damping decrement of the shock circuit, also has a resonant character and is equal to 7 - 8 J at maximum absorption, corresponding at a total particle number on the order of $5 \times 10^{16}$, to an average energy $\bar{\mathcal{E}}$ of the order of 1 keV per ion, just as in the case of the diamagnetic measurements.

An estimate of the value of $T_{\parallel}$ from the half-width of the absorption curves yields $T_{\parallel} \sim 300$ eV, from which we also get, assuming an equilibrium state in the plasma, $\bar{\mathcal{E}} \sim 3T_{\parallel} \sim 1$ keV.

It is characteristic, unlike in experiments with a cold-electron plasma [1], that under the conditions of our experiments the decay time of a plasma with $T_e \sim T_i \sim 1$ keV differs only slightly from the case $T_e \gg T_i$.

[1] W. M. Hooke and M. A. Rothman, Nucl. Fusion 4, 33 (1964).

[2] S. Yoshikawa, R. M. Sinclair, and M. A. Rothman, Ion Heating in the Model C Stellarator, Intern. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, 1965.

[3] L. V. Dubovoi and V. P. Fedyakov, DAN SSSR 167, 553 (1966), Soviet Phys. Doklady 11, 239 (1966).

# E r r a t a

Article by L. V. Dubovoi et al., Vol. 4, No. 10, p. 264.

The abscissas of Fig. 2 represent $B_0$ in kOe.