PLASMA HEATING BY A HIGH-AMPLITUDE ION-CYCLOTRON WAVE

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We describe experiments devoted to an investigation of the efficiency of plasma heating by a high-amplitude ion-cyclotron wave. The experiments make use of a hydrogen plasma which is preheated to a temperature of 1 keV by electrons. An anomalously strong damping of the high-amplitude ion-cyclotron wave has been observed. In a time less than 10^{-6} sec the total energy of the wave is converted to thermal motion of the particles; under optimum conditions the plasma receives up to 70% of the energy stored in the shock circuit that generates the wave. For a particle density of the order of 10^{13} cm^{-3} the energy density in the plasma, obtained as a result of heating, is $n(T_e + T_i) \sim 2 \times 10^{16}$ eV/cm^3. The experiments have been carried out in mirror systems.

THE random micropulsations of the electric and magnetic fields that are found in a turbulent plasma in most present-day confinement systems lead to an anomalously rapid diffusion of charged particles across the confinement magnetic field; this diffusion is characterized by a time τ which satisfies the semi-empirical Bohm-Bishop formula:[1]

$$\tau \sim \tau_B = \frac{\pi a^2 e H_z}{ckT_e} R;$$

where a is the radius of the system, H_z is the magnetic field, T_e is the electron temperature, and R is a numerical factor ranging between 1 and 10.

In accordance with this relation, one expects that in the initial investigations of methods of stabilization of the most dangerous forms of kinetic instabilities in a dense $n \gtrsim 10^{14}$ cm^{-3} high temperature ($T_{e,i} \approx 10$ keV) plasma for which $H_z \approx 10^4$ g the experimental value of τ will not exceed 10^{-3} sec. In order to obtain a plasma with these parameters the duration of the heating process δt must satisfy the obvious requirement

$$\delta t \lesssim \tau \sim 10^{-3}\text{ sec.}$$

The power W required for this purpose for the plasma heating generator can be obtained from the energy balance equation

$$W\delta t = n(T_e + T_i)V,$$

where V is the volume occupied by the plasma. If $V \sim 10^5 - 10^6$ cm^3, as is typical for most large scale devices, we find that the quantity W is $10^8 - 10^9$ watts. At the present time, power levels of this kind in pulsed operation are realistic from the technical point of view, but the use of conventional high-frequency methods for heating plasma in a magnetic field requires additional experimental and theoretical work. Verification of this kind will be unavoidable, in particular, in view of the fact that the introduction of $W \sim 10^8 - 10^9$ watts into a trap means that the heating field and the confinement field become comparable in magnitude, in which case the interaction of the high-frequency fields with the plasma becomes highly nonlinear. Furthermore, under these conditions one expects the appearance of new kinds of instabilities, which will be characteristic for a given method of heating.

Inasmuch as these effects have not been investigated to any great extent for resonance heating methods, and since their influence on the efficiency of heating can be expected to be decisive in a given scheme for producing a hot dense plasma, it will be evident that one should carry out experiments designed to investigate these questions.

In the present work, which is an extension of the work reported in [2,3], we have investigated experimentally the generation and absorption of an ion-cyclotron wave [4] in which the amplitudes of the variable component of the magnetic field H_z in the region of the excitation circuit amount to 0.5 to 0.6 of the stationary confinement field H_z = 2.13 kg. A schematic diagram of the experimental arrangement is shown in

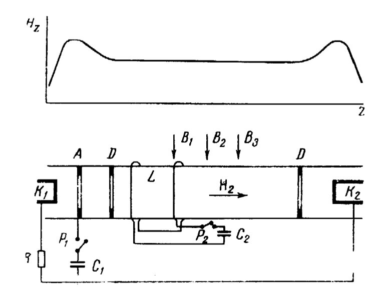

FIG. 1. Block diagram of the apparatus (terminology given in text). The diamagnetic probe is located near the probe B_3.

These experiments have been carried out in magnetic mirror devices. The field H_z in the uniform portion of the mirror system, 100 cm in length, can be varied from 1 to 10 kg while maintaining a mirror ratio of 1.4. The transverse dimensions of the plasma columns are bounded by two glass limiters D (cf. Fig. 1) with apertures for which d = 7 cm. The plasma is produced in a quartz tube 11 cm in diameter and the operating gas is hydrogen at an initial pressure of 2×10^{-4} Torr. The discharge electrodes K_1 and K_2 are fabricated from aluminum. The neutral gas is injected through a series of small apertures in a central region of the cathode K_1. The system is evacuated near the electrode K_2.

The methods of measurement are the same as those described in [2-5]. The basic diagnostics use an 8-mm microwave signal, measurements of the diamagnetic signal, and estimates of the temperature and density of the ion component by means of a system of magnetic probes which measure the time and space characteristics of the low-amplitude ion-cyclotron wave. The diamagnetic effect is measured by the reduction of the total magnetic flux $\delta\Phi_Z$ in the plasma column.

Preliminary ionization of the gas in the system is realized by applying a voltage pulse to the ring electrode A. The PIG discharge which arises in the free electrode system K_1AK_2 with the limiting resistance R = 1 k ohm in the short arm K_1A produces ionization sufficient for initiation of a straight discharge in the gap AK_2 the current of which is limited only by the characteristic impedance $\rho \ll R$ of the capacitor circuit $C_1 = 0.5\ \mu F$, the inductance of the plasma column with the reverse current conductors, and the discharge gap P_1. If the peak values of the current in the arm AK_2 are higher than 20–30 kA (with an oscillation period $T \approx 2 \times 10^{-6}$ sec and a discharge length or order 5T) conditions are created in the system for which it is possible to realize turbulent heating of the electrons.[2,3,5] Up to the time of complete damping of the current in the arm AK_2 there is produced in the trap a plasma with a particle density $2 \times 10^{13}\ cm^{-3}$, $T_e \approx 10^3$ eV, and $T_i \approx 10^2$ eV.[3]

The measurements indicate that at the time the ion-cyclotron wave generator is turned on the hydrogen is essentially fully ionized; it can be assumed that the processes that occur in the plasma are of a collisionless nature. The lifetime of the plasma with the hot electrons [$\tau \approx 30\ \mu sec$], as determined independently of the decay of the density and diamagnetic signal, is of the order of the computed value $\tau_B \sim 10^{-5}$ sec. Since the electron heating process does not last any longer than $\delta t \sim 10\ \mu sec$, it is always true that $\delta t < \tau$.

An ion-cyclotron wave of high amplitude is excited by means of the ringing circuit C_2L. The value of the capacity $C_2 = 0.05\ \mu F$, the frequency $f_0 = 2.4$ MHz and the initial stored energy $Q_0 = \frac{1}{2} CU^2 = 10J$. The ac current in the inductance L generates long-wave oscillations in the plasma[4] $\lambda = 40$ cm. The coil is located close to one of the mirrors. The oscillations of the electromagnetic field that arise as a result of the shock excitation of the circuit propagate along the region of the trap characterized by uniform H_Z. The magnitude of the longitudinal component $\tilde{H}_Z$ and the phase velocity of the wave V_{ph} are measured by a system of magnetic probes B located along the chamber. The shock excitation circuit is switched on some 5–10 μsec after the termination of the electron heating process in the direct discharge. The time for the generation of the wave packet is $\delta t \sim 10^{-6}$ sec and the experimental conditions are such that the relation $\delta t < \tau$ is always satisfied.

In Fig. 2 we show a sequence of switching of both systems for heating in time characterized by the measurement of the reduction in the total magnetic flux $\delta\Phi_Z(t)$ and the computed value of the energy density in the plasma $n(T_e + T_i)$. The first peak $\delta\Phi_{Z1}$ corresponds to the preliminary heating stage in the dc current discharge while the second peak $\delta\Phi_{Z2} \approx \delta\Phi_Z - \delta\Phi_{Z1}$ is due to the heating of the plasma by the surge circuit C_2L.

In order to determine the fraction of the energy acquired from the circuit in ion-cyclotron wave generation we have taken measurements of the damping decrement as a function of H_Z for the ratio of the power W introduced into the plasma to the power W_0 consumed in the circuit (Fig. 3). We also show the dependence of the ratio $\delta\Phi_{Z2}/\delta\Phi_Z$ on H_Z. It is evident that each of the curves has two sharp maxima located in the region of exact resonance for atomic hydrogen $f_c \equiv eH/2\pi M_i c \equiv f_{ci}$ and in the region $f < f_{ci}$ where the theory[4] predicts the optimum conditions for the generation of the ion-cyclotron wave. The curve $W/W_0(H)$ indicates that at absorption maxima the resonant transfer of energy to the plasma reaches $0.7Q = 7$ J.

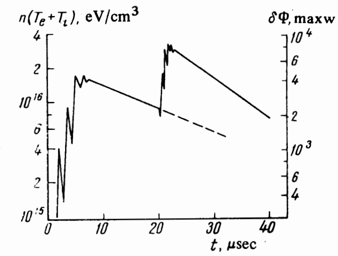

FIG. 2. The diamagnetic effect in the plasma as a function of time for two-stage heating of the plasma.

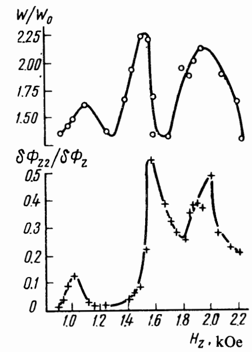

FIG. 3. Efficiency of plasma heating by the high-frequency field of the circuit for various values of H_Z.

The magnetic probe measurements and the resonance nature of the curves in Fig. 3 indicate that in the region of the second peak the high-frequency energy absorbed from the surge circuit goes into the generation of the ion-cyclotron wave. From the difference in the values of the magnetic field H_Z at the points of maximum absorption we can estimate the ion density[4]: $\eta_i \approx 10^{13}\ cm^{-3}$ whence, the energy absorbed in the plasma 7 J for the volume occupied by the plasma $V \approx 4 \times 10^3\ cm^3$ yields the mean energy increment going into each electron-ion pair: $\delta(T_e + T_i) \approx 10^3$ eV. Independent measurements of the diamagnetic signal $\delta\Phi_{Z2}$ yield similar values $\delta(T_e + T_i) \approx 10^3$ eV.

In Fig. 4 (from the top down) we show oscillograms of the measured values of $\tilde{H}_Z(z, t)$ for the ion-cyclotron wave at the point z = 0 which correspond to the plane of the turn of the coil furthermost to the right (cf. Fig. 1) and at the points $z = \lambda/4$ and $z = \lambda/2$ where λ is the wavelength, 40 cm. For greatest clarity in examining the features of the damping process of the front part of the wave packet for maximum values of $\tilde{H}_Z$, the second two oscillograms have a phase shift $\delta\Phi = z/V_{ph}$ with respect to the first; also, the gain for each of the probes has been chosen so that

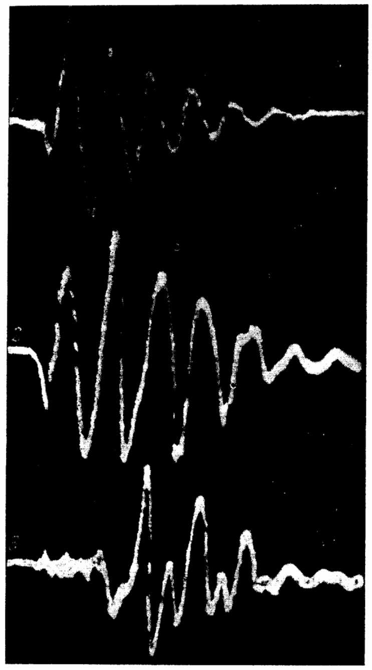

FIG. 4. Oscillograms showing the magnetic field of the wave at the following points: 1) $z = 0$, 2) $z = \lambda/4$, 3) $z = \lambda/2$ ($\lambda = 40$ cm).

the amplitude scales for the fields in the corresponding half-cycles of the trailing part of the packet are approximately the same for each of the pictures.

The oscillograms have been obtained in the region of the second absorption maximum for the energy of the rf circuit corresponding to conditions for the generation of the maximum amplitude wave. It is evident that with the exception of the first half-cycle (the anomalous form of which is associated with the time delay in the switching system) the peak values of the field $\tilde{H}_z(0, nT/4)$ (where $n = 1, 3, 5, \ldots, T$, is the oscillation period) decay exponentially. At the same time $\tilde{H}_z(\lambda/4, t)$ for $n < 9$ exhibits a clear deviation from the exponential dependence characteristic for $\tilde{H}_z(0, t)$ and $\tilde{H}_z(\lambda/4, t)$ for $n > 9$.

The anomalies in the wave damping process and the threshold nature of this effect are especially clear from the curve $\tilde{H}_z(\lambda/2, t)$ where only the trailing edge has been retained; the energy of the first five half-cycles is completely dissipated in the plasma and the times $t > 5T/2$ are characterized by the appearance of higher harmonics with frequencies that are multiples of the given signal.

These curves can be used to find the energy dissipated as the wave propagates along the plasma column as a function of the quantity $\tilde{H}_z$. An idea of the efficiency of the absorption of the ion-cyclotron wave under the experimental conditions can be obtained by observing the damping of the field $\tilde{H}_z$ in each half-cycle following the traversal of a distance $z = \lambda$ by the wave packet. In Fig. 5 we show the experimentally determined ratio $X = \tilde{H}_z(0, nT/4)/\tilde{H}_z(\lambda, nT/4)$ as a function of $H_z(0, nT/4)$. for the points $n = 1, 3, 5, \ldots$. It is evident from Fig. 5 that the wave propagation is characterized by a critical amplitude $\tilde{H}_z$ which depends on the nonlinearity parameter $s = \tilde{H}_z/H_z$; starting at

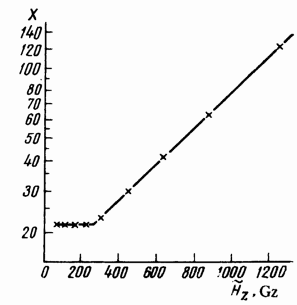

FIG. 5. The wave absorption as a function of wave amplitude: H_0 = 2.13 kOe.

this value the energy damping process in the corresponding half-cycles of the wave packet becomes a strong function of $H_z(0, nT/4)$ while the observed damping length can be of the order of or smaller than the diameter of the plasma column. When $s < 0.2$ the quantity X = const and it may be assumed that the observed damping, at least qualitatively, corresponds to the conditions for the propagation of the ion-cyclotron wave at low amplitude.[4]

Difficulties associated with the nonlinearity of the problem and the fundamental transient nature of the process (exponential damping of the excited wave and a sharp change in the ion temperature with a characteristic time $\delta T \sim T$) make it essentially impossible to carry out an analysis of these results for $s < 0.2$. In this region $X(\lambda) \gg 1$ and the theory [4] is no longer applicable; for this reason the nature of the observed anomalous damping of the high amplitude wave cannot be understood without additional detailed calculations.

One possible origin for the effect observed here may be a mechanism similar to that reported in [6] where, in the linear approximation, a case was investigated for the threshold decay of the ion-cyclotron wave of large amplitude into waves of two other kinds. Support for this mechanism is indicated by the intense ordered electromagnetic oscillations observed in the experiment, this radiation being regularly excited against the background field of the basic wave. A possible mechanism that might apply to our conditions for a magnetized plasma is discussed in [7]; this mechanism is based on the fact that the ion-cyclotron heating method leads to a strong anisotropy of the ion velocity. In both cases one must introduce a process for effective randomization of the directed motion of the particles in the wave with a rapid destruction of the wave structure.

Probe measurements and the resonance nature of the dependence $W/W_0 = f(H_z)$ and $n(T_i + T_e) = \chi(H_z)$ obtained experimentally furnish evidence that the energy transferred from the surge circuit to the plasma goes into the generation of an ion-cyclotron wave of high amplitude with the subsequent conversion of the wave energy into thermal motion of the particles. Unfortunately, the diagnostic techniques used in the present work do not allow a unique determination of the fraction of the energy of the cyclotron wave that is transferred directly to the plasma ions. For this reason it is desirable to make an estimate of the probable value of the ion energy in the plasma obtained in these experiments.

We assume, as in the case of low-amplitude waves,[4,8,9] that when $S \sim 1$ only the ions are heated; it then follows from the data given above that the maximum possible experimental value $T_i \sim 1$ keV, the plasma is isothermal, the containment time for the particles τ for $T_e > T_i$ is of the same order as τ for $T_e \sim T_i$. It is characteristic that under these conditions the ion-cyclotron radius $r_{ci} \sim 2\text{cm} \sim d/2$ in which case it may be assumed that the magnetic field has only a weak effect on the ions. In accordance with the usual condition of quasi-neutrality, the plasma ions in the trap are confined only by the space charge due to electrons contained by the magnetic field while the loss of particles must be in accordance with the requirements of ambipolar diffusion with a characteristic time for the existence of the magnetized state of the electrons given by $\tau \gtrsim \tau_B$. The minimum value $T_i \sim 10^2$ eV for $T_e \sim 2$ keV is obtained if one assumes the least likely case, that all the energy of the directed motion of the ions goes entirely into heating of the electrons.[3]

Let us assume in the experiments on turbulent interaction of beams with a plasma that, in addition to leveling the velocity distribution function the particles also retain a considerable fraction of the initial energy of the directed motion; one then expects that under the conditions of the present experiment the anomalous dissipation of the ion-cyclotron wave will also be accompanied by an appreciable heating of the ions.

In connection with the importance of the question of heating efficiency for ions by the cyclotron wave of large amplitude, at the present time we are developing methods for measuring the energy distributions for the electrons and ions that escape from the trap through the mirrors. It is of great interest to develop a theoretical analysis of the probable mechanisms for the anomalous dissipation of the high-amplitude ion-cyclotron wave for conditions approximating those of the experiment.

Inasmuch as the inequality $\delta t < \tau$ is always satisfied for both heating cycles, the effects observed in this work do not depend on the thermal isolation properties of the particular trap used in the experiment.

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