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PLASMA HEATING BY A FAST MAGNETOSONIC WAVE OF LARGE AMPLITUDE

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We have investigated resonance excitation and absorption of the fast magnetosonic wave in a hydrogen plasma in the frequency range $\omega_i \lesssim \omega \ll \sqrt{\omega_i\omega_e}$ (ω_i and ω_e are the ion and electron cyclotron frequencies and ω is the wave frequency) at a plasma density of 10^{13}–10^{14} cm^{-3}. The alternating field in the plasma is generated by means of a coil consisting of several sections, with alternate sections being connected in phase opposition. The coil comprises the inductance in a shock-excited circuit with a stored energy up to 10 J at a frequency of 7×10^6 Hz. With resonance excitation of the fast magnetosonic wave up to 70% of the energy stored in the circuit is transferred to the plasma. Under these conditions the peak value of the alternating magnetic field in the plasma is 500 Oe. The electrons experience a rapid ($\lesssim 1$ μsec) heating to a mean energy of approximately 200 eV while the ions are heated to approximately 20 eV. Measurements have been made of the velocity distributions for the ions and electrons that escape from the plasma along the fixed magnetic field; these measurements have been made at small and large values of the RF field. Possible mechanisms responsible for the observed wave damping and plasma heating are discussed.

1. INTRODUCTION

INTEREST in the excitation and absorption of fast magnetosonic waves in the plasma stems from the fact that at large amplitudes these waves can be used for heating plasmas with densities of 10^{13}–10^{15} cm^{-3};[1] the same waves, at low amplitude, can be used for diagnostics of a high-temperature plasma.

A number of authors[2-4] have given theoretical analyses of the mechanisms responsible for damping of the fast magnetosonic wave at low amplitude in a plasma (Cerenkov absorption and ohmic absorption in the surface layer). In[2] criteria are stated for the applicability of the linear theory for Cerenkov absorption of these waves; estimates of the rate of Cerenkov heating of the electron by a low-amplitude wave are also given.

Experimental work[5-8] has shown good agreement with the linear theory of excitation, propagation and damping of the fast magnetosonic wave in plasmas characterized by different parameters. In particular, measurements of the wave damping length[7] are in order-of-magnitude agreement with calculations carried out for Cerenkov absorption by electrons. It has been shown experimentally[1] that it is possible to heat hydrogen and helium plasmas by a fast magnetosonic wave of low amplitude; electron and ion energies of the order of 150 eV have been obtained.

The present work describes an experimental investigation of resonance excitation and absorption of the fast magnetosonic wave in a plasma in the frequency range $\omega_i \lesssim \omega \ll \sqrt{\omega_i\omega_e}$ where ω is the wave frequency while ω_i and ω_e are the ion and electron cyclotron frequencies respectively. Waves of large amplitude have been used; according to the theory of Cerenkov absorption the absorption can be reduced significantly as a consequence of the formation of a plateau on the electron velocity distribution function.[9] On the other hand, in the transverse electric field produced by a wave it is possible to have a two-stream instability.[10] The ratio of amplitudes of the RF magnetic field of the wave H_z and the fixed magnetic field H_0 was always smaller than unity so that the nonlinear effects described in[11], which lead to the production of an oblique shock wave, were not observed under the present experimental conditions.

In addition to the high amplitude of the RF field, a new feature of the experiments described here is the short lifetime of the RF pulse used to excite the fast magnetoacoustic wave. This short lifetime makes it possible to realize a great simplification in the technology used for generation of the alternating fields of large amplitude. In this case it is possible to use a shock-excited circuit in place of the rather complicated configurations that are required when a vacuum-tube generator is used. Furthermore, because of the short lifetime of the RF field, during the time in which the plasma is heated there are no significant particle losses due to the anomalous decay which has been observed in[7].

Certain preliminary results of experiments on the excitation and absorption of a fast magnetosonic wave of high amplitude in the plasma carried out in helium have been described in[12,13].

APPARATUS AND METHOD OF MEASUREMENT

These experiments were carried out on an apparatus shown schematically in Fig. 1. The plasma is produced in a pulsed Penning discharge (current pulse 18 μsec) in hydrogen at pressure of the order of 10^{-3} mm Hg. The internal diameter of the glass discharge tube is 6 cm and the distance between cathodes is 88 cm.

A quasistatic magnetic mirror field H_0 is characterized by a uniform region in the center section, this region being 70 cm in length (the effect of the mirror geometry on plasma heating has not been studied in the present work). The field strength can be varied from 200 to 6000 Oe. The largest magnetic field obtained in a given series of measurements depends on the maxi-

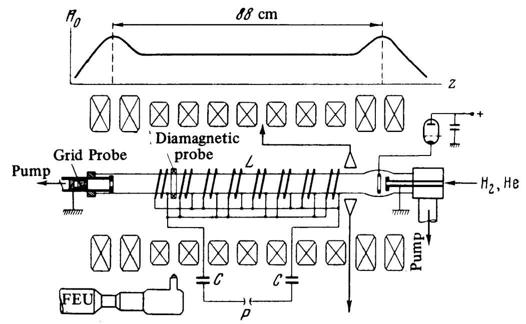

FIG. 1. Diagram of the apparatus

mum electron density reached in the measurements (as a rule this density does not exceed 10^{14} cm^{-3}). The relation between the density and magnetic field for resonance excitation of the fast magnetosonic wave is contained in the dispersion relation (1) (cf. below).

The source of RF energy is a shock-excited circuit with a stored energy up to 10 J which is triggered by a discharge gap P. The inductance of the circuit L is due to the eight individual sections which are wound on the discharge tube and driven by the capacitor C. Alternate sections are connected in phase opposition. The axial period of the electromagnetic field generated by the coil is characterized by $\lambda = 20$ cm. The oscillation frequency of the circuit is 7 MHz and the Q without plasma is 35; the maximum value of the field H_z at the axis of the system is 300 Oe in vacuum.

A comparison of the damping coefficients for the oscillations in the circuit in the presence of plasma and without plasma makes it possible to estimate the energy transferred to the plasma. In the present case it is convenient to introduce the notion of a transfer coefficient: this coefficient is defined as the ratio of the RF energy absorbed in the circuit in the presence of a plasma (subtracting off the ohmic losses in the circuit itself) to the total energy stored in the condenser before it is triggered. Under the assumption that the circuit oscillations are damped exponentially, the transfer coefficient can be defined as $\alpha = 1 - N_1/N_0$ where N_1 and N_0 are the number of oscillation cycles in which the amplitude is reduced by a factor e = 2.72 in the presence of a plasma and without plasma.

The high-frequency field at the axis of the system H_z is measured with a magnetic probe with an external diameter of 5 mm; this probe is wound inside a glass tube that is inserted into the discharge along the axis.

The average (over the cross-section of the tube) electron density in the plasma is measured by microwaves at wavelengths of 8 and 2 mm. It is observed that in the absence of external electric fields, in the density range 10^{12}–10^{14} cm^{-3} the plasma decays exponentially with a decay constant that depends on the strength of the quasistatic magnetic field H_0. In the majority of experiments this makes it possible to use the 8-mm interferometer, in which case densities higher than 1.7×10^{13} cm^{-3} are determined by extrapolation.

The measurement of the longitudinal energies of the electrons and ions that escape from the plasma along the field is carried out by means of a triple-grid analyzer that uses retarding potentials. This probe is located beyond one of the cathodes in the plasma source. The measurements are carried out by determining the dependence of electron or ion current to the collector as a function of the retarding potential. Using the volt-ampere characteristics obtained in this way, by differentiation it is possible to find the velocity distribution function for the corresponding particles, and thus to determine the mean particle energy.

It should be noted that in analyzing the dependence of ion current on retarding potential we do not take account of the finite transit time of the ions from the plasma to the probe-collector. This time is comparable with the length of the RF pulse so that the values of ion energy measured by the analyzer at different times can be somewhat different from the true ion energy in the plasma at a given time.

The transverse plasma pressure is measured by means of a diamagnetic probe; this probe is a coil consisting of 300 turns wound on the discharge tube between two adjacent sections of the RF circuit. The probe signal is integrated in the RL circuit formed by the inductance of the probe and a load resistance.

The H_β emission line from hydrogen in the discharge is detected by means of a UM-2 monochromator and a photomultiplier.

3. BASIC RESULTS

A. In these experiments the plasma source is switched on at the time the quasistatic magnetic field reaches its peak value. The RF circuit is triggered after the discharge current is terminated, while the plasma decays. Under these conditions no indications of plasma instabilities are observed. The delay time in triggering the shock-excited circuit with respect to the time at which the discharge current in the Penning discharge is terminated is dictated by the desired initial plasma density in which the fast magnetosonic wave is to be excited.

The sequence of operations is shown in Fig. 2. In this figure we show oscillograms of the intensity of the H_β light from hydrogen and show the dependence of electron density n_e on time. The time origin t = 0 is taken to be the time at which the discharge current that produces the plasma is switched on. The initial hydrogen pressure is approximately 10^{-3} mm Hg, the initial plasma density $n_0 = 3 \times 10^{12}$ cm^{-3} and the strength of the quasistatic magnetic field $H_0 = 400$ Oe. It is evident

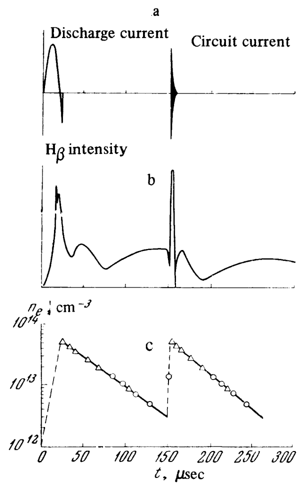

FIG. 2. Time sequence of operations (a) and the intensity of the H_β emission line (b) and the electron density (c) as functions of time; Δ values of density obtained with the 2 mm interferometer, O with the 8 mm interferometer.

from the figure that during the time in which discharge current flows the degree of ionization of the plasma reaches something of the order of several tens of percent.

After the termination of the discharge current in a time of approximately 50 μsec the plasma temperature falls to ~0.1 eV as indicated by the peak in the H_β radiation due to the recombination of the population of the excited levels (predominantly as a consequence of three-body recombination[14]). Simultaneously there is a reduction in the plasma density, this being characterized by a decay constant of approximately 60 μsec. The validity of this analysis of the behavior of the H_β radiation in time is supported by the following: after the RF field is switched on, as follows from Fig. 2b, the intensity of the H_β radiation begins to diminish (in[14] it is shown that the strength of the recombination process in the excited levels is proportional to T_e^{-n}, where $n > 1$); it then goes through a minimum and reaches a peak caused by excitation by electron impact. After reaching this peak the H_β emission is reduced essentially to zero as a result of "heating" of the neutral gas. The validity of the assumption that the hydrogen is essentially completely ionized after the RF circuit is operated is also supported by an estimate of the ionization time if one starts with some typical experimental values for the initial hydrogen pressure, the initial electron density, and the mean electron energy after the circuit is operated (cf. below Fig. 10). According to this estimate the ionization time is of the same order (1 μsec) as the time for "burnout" of the H_β line (cf. below Fig. 7). Further support for the almost complete ionization of the gas following the operation of the shock-excited circuit is also provided by comparing the initial pressure of the neutral gas with the final electron density in the plasma.

When the circuit current stops the plasma experiences cooling and decay accompanied by the production of two peaks in the H_β radiation, the first being due to the excitation by electron impact and the second to recombination in the excited levels.

This is the general pattern of the plasma behavior in the course of a pulse.

B. The experiments described in the present paper can be divided in two groups. The first group comprises experiments on the excitation of the fast magnetosonic wave and an examination of its dispersion properties. For this purpose we determine the dependence of the transfer coefficient on the strength of the magnetic field for several fixed values of the initial plasma density. A family of absorption curves obtained in this way is shown in Fig. 3. It is evident from this figure that for a given value of the initial density the absorption of RF energy in the plasma exhibits a resonance. The peak in each absorption curve corresponds to a magnetic field for which the inequality $\omega_i < \omega \ll \omega_e$ is satisfied.

The dispersion equation for the fast magnetoacoustic wave in a low-pressure plasma in the appropriate range of frequency and density can be written in the form[15]

$$\omega_i^2/\omega^2 = 2/r\{1+\cos^2\theta + r\cos^2\theta + [(1+\cos^2\theta + r\cos^2\theta)^2 - 4\cos^2\theta]^{1/2}\}, \tag{1}$$

where $r = k^2c^2/\Omega_i^2$, Ω_i is the ion-plasma frequency; $\cos^2\theta = k_{\|}^2/k^2$, $k^2 = k_{\|}^2 + k_{\perp}^2$; $k_{\|} = 2\pi/\lambda$ is determined by the axial period of the coil λ; the quantity $\lambda_\perp$ is found from the boundary conditions. For the case of an infinitely long plasma cylinder surrounded by a metal wall we have $k_\perp = \mu_1/R$ where $\mu_1 = 3.8$ .... is the first root of the Bessel function $J_1(k_\perp R)$ (R is the wall radius). For a plasma cylinder in vacuum $k_\perp$ can be found from the dispersion equation in[16]. For the actual case (a plasma that is inhomogeneous in radius in a glass tube on which the coil is wound) an exact knowledge of the boundary conditions is difficult to obtain, the more so since the plasma density varies during the course of an RF pulse. It is reasonable to assume that the dispersion curve corresponding to the true boundary conditions lies somewhere between the two curves corresponding to the two sets of boundary conditions considered above.

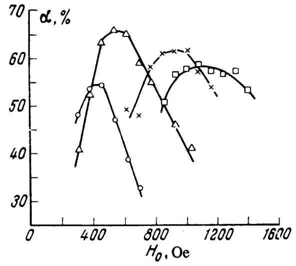

FIG. 3. The coefficient of energy transfer as a function of magnetic field for a plasma with the following initial densities: ○ – 1.7 × 10^{13}, Δ – 2.0 × 10^{13}, × – 3.0 × 10^{13}, □ – 4.5 × 10^{13}.

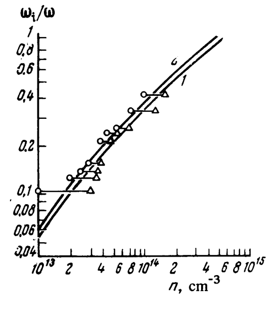

FIG. 4. Ratio of the ion-gyro frequency to the operating frequency as a function of plasma density.

In Figure 4 we show the ratio ω_i/ω as a function of the plasma density n as computed from Eq. (1). The curve marked 1 is plotted for the case of a plasma in a metal chamber ($k_\perp \approx 1\ cm^{-1}$; R = 3.8 cm is the coil radius) while the curve marked 2 ($k_\perp \approx 0.88\ cm^{-1}$) corresponds to a plasma of radius 3 cm surrounded by vacuum. The experimental points are plotted on the graph, these points corresponding to the absorption maxima. Each ordinate corresponds to a pair of points; the left point (circle) indicates the abscissa for the initial density and the right point (triangle) indicates the maximum density observed after the circuit is operated. The value of the final density depends on the initial pressure of the neutral gas in a given series of measurements. It is evident from Fig. 4 that the experimental points are in good agreement with the theoretical de-

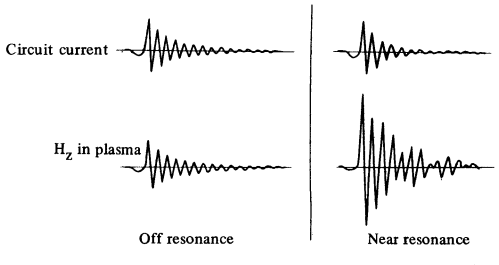

FIG. 5. Oscillograms of the current in the circuit and the RF magnetic field in the plasma.

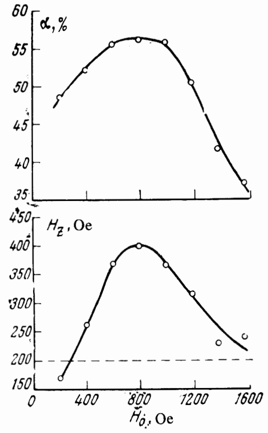

FIG. 6. The coefficient of energy transfer and the amplitude of the RF magnetic field in the plasma as functions of the fixed magnetic field.

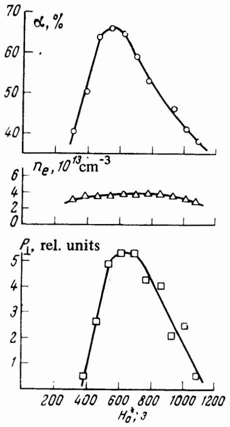

FIG. 8. Energy transfer coefficient, electron density, and transverse pressure in the plasma as functions of the fixed magnetic field.

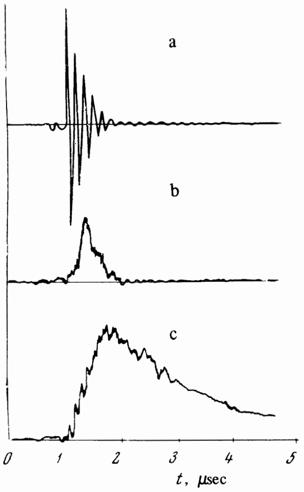

FIG. 7. Oscillograms: a) RF circuit current, b) H_β line intensity and c) diamagnetic signal in the plasma at resonance

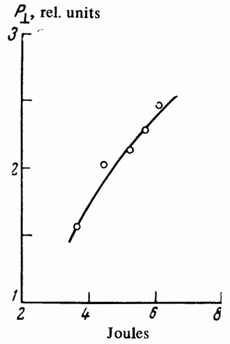

FIG. 9. Dependence of transverse pressure on RF energy abosrbed by the plasma.

pendence expected for the fast magnetosonic wave.

The increase in the absorption of RF energy in the plasma in resonance excitation of the fast magnetosonic wave is due to the increase in the RF field in the plasma that occurs when the axial period of the current in the coil coincides with the longitudinal wavelength in the plasma.[16] This effect is shown in Fig. 5 in which we present an oscillogram of the current in the circuit and the strength of the RF magnetic field H_z in the plasma on the axis of the system for two values of H_0; one value is far from the resonance value and the other is in the resonance region for the specified initial density. Far from resonance the oscillogram of H_z is similar to the oscillogram for the current in the circuit (with the appropriate gain on the Y-axis of the oscilloscope); near resonance the field H_z indicates an amplification.

In Fig. 6 we show the dependence on H_0 of the peak value of H_z in the plasma (on the axis of the system under one of the sections of the circuit coils) and the transfer coefficient α. The value of H_z has been taken to be the peak value in the second half cycle. The dotted line in the lower curve denotes the corresponding value of H_z when no plasma is present. As expected, the functional dependence $H_z(H_0)$ and the functional dependence $\alpha(H_0)$ both show a resonance effect and the peaks of these two quantities occur at approximately the same values of the fixed magnetic field.

B. In a second group of experiments we have examined the properties of the plasma when a high-amplitude fast magnetosonic wave is excited. In Fig. 7 we show oscillograms of the circuit current, the strength of the H_β line, and the diamagnetic signal in the plasma under resonance conditions. It follows from Fig. 7 that after four or five cycles of the RF field, that is to say, up to the time of almost complete transfer of RF energy to the plasma ($\lesssim 1$ μsec), the emission of the H_β line goes through a peak and then falls almost to zero. It can be assumed that during this time the degree of ionization of the plasma is almost 100%. The diamagnetic signal reaches a peak value during the same time period. These data indicate rapid heating of the electrons by the RF field.

In Fig. 8 we show the dependence of H_0 of the transfer coefficient, the maximum density, and the energy of the transverse motion of the plasma particles. These measurements are carried out for an initial hydrogen pressure of approximately 5×10^{-4} mm Hg and an initial plasma density of 2×10^{13} cm^{-3}. It is evident from Fig. 8 that in the range of magnetic fields in which there is a substantial absorption of RF energy the transverse pressure of the plasma increases, reaching a peak value at approximately the time of the peak absorption. This effect is due to the increase in the energy of the plasma particles since the terminal density varies insignificantly over this range of magnetic field.

In Fig. 9 we show the transverse plasma pressure $P_\perp$ as a function of the energy absorbed by the plasma. In these measurements the transfer coefficient does not change appreciably as the wave amplitude is increased, remaining at approximately 65%. It follows from Fig. 9 that the transverse pressure increases essentially linearly with energy transferred to the plasma in this energy range. These data are in good agreement with

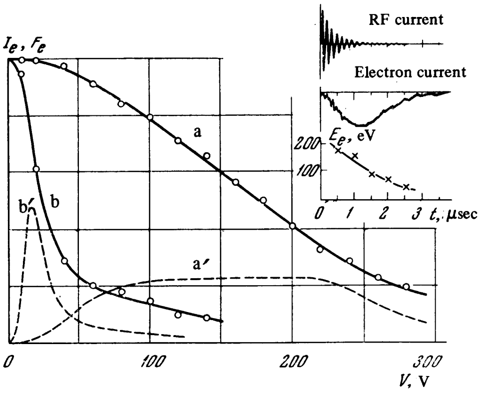

FIG. 10. Electron current to the analyzer collector and the electron velocity distribution function as functions of the retarding potential.

the results of our earlier work[12] in which it has been shown that as the amplitude of the circuit oscillations increases the energy of the particles that escape from the plasma along the fixed magnetic field also increases.

Under resonance conditions, with a circuit voltage of 53 kV (stored energy 6.9 J) the maximum transverse plasma pressure measured by the diamagnetic probe is approximately 4×10^{15} eV/cm^3 in the range of plasma densities ($3 \times 10^{13} - 2 \times 10^{14}$ cm^{-3}) and corresponding magnetic fields that have been studied.

We now present the results of an investigation of the energy distribution of the particles that escape from the plasma along the magnetic field for the case $H_0 = 700$ Oe and a final plasma density of approximately 3×10^{13} cm^{-3}. In Fig. 10 we show the volt-ampere characteristics (solid lines) obtained in measurements of the electron current I_e at various times after the RF circuit is operated. The dashed lines show the distribution functions for the electron velocity F_e obtained by differentiation of the volt-ampere characteristics with respect to the retarding potential. The curves marked a and a′ correspond to times of 0.4 μsec after triggering of the circuit, in which case the oscillation amplitude in the plasma is still large (cf. Fig. 7 and the oscillograms in the upper right insert in Fig. 10). The curves b and b′ correspond to times of 2.5 μsec after initiation of oscillation in the circuit, in which case the oscillation amplitude in the plasma has already been reduced appreciably. Attention is directed to the marked deviation of the function a′ from a Maxwellian. The presence of a plateau on the curve a′ indicates the presence, in the plasma, of high-amplitude RF fields and some process that leads to the smearing of the distribution function for the electron longitudinal velocity. On the other hand the distribution b′ measured in the "quiescent" plasma is essentially a Maxwellian characterized by a temperature of approximately 25 eV. The volt-ampere characteristics taken at intermediate times are intermediate between the shapes of a and b.

In the insert in the upper right of Fig. 10 we show the time dependence of the mean electron energy E_e computed from the volt-ampere characteristics under the assumption that the electron velocity distribution is isotropic. This dependence is in agreement with the time dependence of the plasma energy as determined from the diamagnetic-probe measurements (Fig. 6).

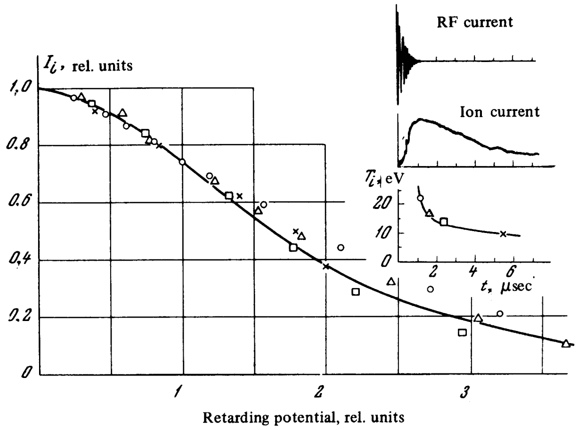

FIG. 11. Ion current to the analyzer collector as a function of retarding potential.

In Fig. 11 we show the results of measurements of the longitudinal ion energy. The solid curve corresponds to the volt-ampere characteristic for a Maxwellian ion velocity distribution (the retarding potential is plotted along the horizontal axis in relative units of eV/T where V is the retarding potential in volts and T is the ion temperature in electron volts). The experimental values obtained at different times are also shown (cf. the curves and oscillograms in the upper right of Fig. 11). It follows from Fig. 11 that the measured ion distribution is approximately Maxwellian even at times close to the beginning of the RF pulse, when the electron distribution function is highly distorted (Fig. 10). The maximum measured ion temperature is approximately 20 eV.

As we have noted above, verification of all data obtained in measurements of ion energy is subject to error associated with the finite transit time required by the ions to travel from the plasma to the detector.

4. DISCUSSION OF RESULTS

We now discuss the question of energy balance in these experiments. Under the conditions shown in Fig. 10 (maximum electron density $n_e \approx 3 \times 10^{13}$ cm^{-3}, quasistatic field $H_0 = 700$ Oe, transfer coefficient $\alpha \approx 65\%$ and a stored circuit energy $W_0 = 6.9$ J) the maximum energy associated with the transverse particle energy in the plasma, which is reached about 1 μsec after the circuit is triggered, is 4×10^{15} eV/cm^3. If we assume that the electron and ion velocity distributions are isotropic, computing the mean energy of an electron-ion pair from the plasma diamagnetic signal we obtain a value of approximately 200 eV. This same value for the mean energy of an electron-ion pair is obtained from independent measurements of the longitudinal particle motion made by means of a multigrid analyzer, also under the assumption that the particle velocity distributions are isotropic. This agreement for mean energies as obtained by two different methods holds for times in which the RF field in the plasma is small and the electron velocity distribution is approximately a Maxwellian as well as for earlier times, when fields of appreciable magnitude exist in the plasma and the electron distribution is very different from a Maxwellian.

The mean energy of an electron-ion pair, 200 eV, indicates that the total kinetic energy of the plasma particles is approximately 1.6 J, amounting to 35% of the RF energy applied to the plasma. Without dwelling in detail on the question of energy losses in the plasma, we note that the losses are very significant, as is indicated by the rapid cooling of the plasma (within a time of 2—3 μsec) after the oscillations are turned off in the circuit. The microwave density measurements indicate that there is not an appreciable loss of particles from the plasma after the oscillations are terminated.

We now consider possible mechanisms that can be responsible for the observed absorption of the fast magnetosonic wave and the rapid randomization of the parallel motion of the particles in the wave field. Knowing the value of the RF energy transferred from the circuit to the plasma we can estimate the damping rate for the wave. The lower limit for the damping rate made on the basis of this estimate yields a value $\gamma_{\mathrm{exp}} \approx 4 \times 10^{-2}\omega$ under conditions of maximum absorption, i.e., with $\alpha = 65\%$. The damping rate determined in this way must be of the same order of magnitude as the true damping for the plasma. This is indicated, as can be seen from Fig. 5, by the fact that the lifetime of the oscillations in the plasma is essentially the same as the lifetime of the RF pulse in the circuit.

There is no doubt that in the earlier heating stages a predominant role is played by heating due to Coulomb collisions (the initial plasma temperature is approximately 0.1 eV). The order of magnitude of the collisional damping factor for the fast magneto-acoustic wave is

$$\gamma_{\mathrm{col}} = \frac{k}{k_{\|}}\left(\frac{\nu}{\omega_e}\right)\omega,$$

where $\nu = \tau^{-1}$ is the electron collision frequency which, under the present experimental conditions, is essentially the frequency of electron-ion Coulomb collisions. An estimate shows that γ_{coll} becomes an order of magnitude smaller than γ_{exp} even when $T_e \lesssim 10$ eV. For the heating rates characteristic of the present experiment this temperature is achieved in a time of the order of 0.1 μsec after the initiation of oscillations in the circuit. It is then evident that collisions cannot be responsible for the absorption of the wave in the plasma for most of the lifetime of the RF pulse.

The possibility of ohmic heating of the plasma by surface currents, which has been considered in[3], is highly unlikely under the present experimental conditions. The measurement of the energy of particles which escape from the plasma along the fixed magnetic field, primarily electrons from the paraxial region, which are farthest from the plasma surface, shows that these acquire a significant energy in a time much shorter than the time between Coulomb collisions.

The linear theory for Cerenkov absorption of whistlers in a collisionless plasma indicates a damping rate $\gamma_{\mathrm{Cer}} \sim (kv_e/\omega_e)\omega$ where v_e is the mean thermal velocity of the electrons.[7] The order of magnitude of γ_{Cer} coincides with that of γ_{exp}. It is known, however, that the linear theory for Cerenkov damping of whistlers holds only if the amplitude of the RF magnetic field in the wave H_z is smaller than a critical value:[2]

$$H_{\mathrm{crit}} \sim H_0(\omega\tau)^{-2/3}.$$

For the conditions shown in Fig. 10 the field H_{crit} is of the order of 10 Oe, that is to say, an order of magnitude smaller than $H_z \sim 100$ Oe, during most of the lifetime of the RF pulse. Thus, the linear theory of Cerenkov absorption of whistlers does not apply in the present case.

A detailed comparison of the experimental results with the quasilinear theory of Cerenkov absorption of the fast magnetosonic wave for conditions of resonance excitation[7] does not appear to be possible since we do not know the radial distribution of plasma density or the excitation spectrum of the waves. It should be noted, however, that according to this theory the distribution of electrons over the velocity component perpendicular to the magnetic field remains fixed in time. Under the conditions of the present experiments, as follows from measurements of the plasma diamagnetism, the electrons acquire a large transverse energy in a time less than τ.

An important contribution to the damping of the fast magnetosonic wave in the plasma can be attributed to collective effects associated with instabilities in the motion of electrons in the transverse electric field of the large amplitude wave. When $H_0 = 700$ Oe and $H_z = 300$ Oe the mean amplitude of the directed electron velocity $u_\perp \sim cE_\perp/H_0$ is of the order of 6×10^7 cm/sec, being much greater than the ion thermal velocity $v_i \sim 4 \times 10^6$ cm/sec but much smaller than the electron thermal velocity v_e.

It has been shown by Stepanov[10] that under these conditions it is possible to excite longitudinal oscillations that propagate almost perpendicularly to the magnetic field, with frequency and growth rate of order $\sqrt{\omega_i\omega_e} \gg \omega$. We can make a numerical estimate of the damping time for the fast magnetosonic wave as a consequence of the excitation of this instability. With $u_\perp \approx 6 \times 10^7$ cm/sec the mean energy density acquired by the electrons in the wave field is $nmu_\perp^2/2 \approx 30$ erg/cm^3 and the energy density of the wave is $H_z^2/8\pi \approx 4 \times 10^3$ erg/cm^3. If we assume that in a time of order $(\sqrt{\omega_i\omega_e})^{-1}$ all of the energy of the directed motion of the electrons goes into excitation of oscillations, the damping time for the magnetosonic wave t_{damp}, defined as the time in which there is a complete transfer of electromagnetic energy of the wave into the fine-scale oscillations excited by the beam, is

$$t_{\mathrm{damp}} = H_z^2/4\pi m u_\perp^2\sqrt{\omega_i\omega_e} \approx 2\cdot 10^{-7}\ \mathrm{sec},$$

that is to say, it is of the same order as the measured damping time for the oscillations in the circuit.

It also follows from[10] that under the present experimental conditions the electron beam formed in the transverse electric field of the wave can excite fine-scale oscillations with frequency and growth rate of the order of the ion-plasma frequency. An estimate of the damping rate of the fast magnetosonic wave due to the excitation of these oscillations gives a damping time that is the same as that considered above.

Thus the assumption that the damping of the fast magnetoacoustic wave of large amplitude is due to the excitation of fine-scale RF longitudinal oscillations does not contradict the experimental data obtained in the present work. In order to form more definite judgements as to the role of these instabilities in wave damping it will be necessary to investigate the plasma noise spectrum.

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