Observation of collisionless electron-cyclotron damping in a plasma

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The collisionless cyclotron damping of a transverse wave near electron-cyclotron resonance is measured in well-defined experimental conditions. The observed wave dispersion and damping are in good agreement with a hot-plasma theory. It has been revealed that spatial damping rates are determined by only one parameter, i.e., the ratio of resonance velocity to the thermal velocity.

Electron-cyclotron damping in a uniform hot collisionless plasma is an important fundamental process in rf plasma heating. However, it has not yet been clearly verified in the experiment, in contrast to a clear-cut experiment[1] on electron Landau damping of longitudinal waves. Olson[2] has demonstrated several criteria for accurate measurement of spatial cyclotron damping of transverse waves [right-hand circularly polarized (RHCP) waves]. Many pioneering attempts[3-7] to observe the cyclotron damping have violated at least one of his criteria, in point of dominant collisional effect,[3-5] low electron temperature,[6] density and magnetic field gradient.[7] In this paper, we present the first experimental evidence which confirms cyclotron damping of a RHCP wave near resonance. A useful simple expression for the cyclotron damping rate is derived on the analogy of Landau damping and established in the well-defined experiment.

For a Maxwellian electron distribution, the dispersion relation of the RHCP wave propagating parallel to a magnetic field is given by

$$[(ck/\omega)^2-1](\sqrt{2}\omega k v_T/\omega_p^2)=Z(\zeta)\,, \qquad (1)$$

where $\zeta=(\omega-\omega_c+i\nu)/\sqrt{2}kv_T$, electron thermal velocity $v_T=(\kappa T_e/m)^{1/2}$, ν is an effective collision frequency, and Z is the plasma dispersion function.[8] Spatial collisionless damping is obtained for complex wave number $k=k_r+ik_i$, real frequency ω, and $\nu=0$. This damping rate can only be obtained numerically since an asymptotic expression analogous to Landau damping does not exist.[2] Therefore, Eq. (1) is inconvenient to physical interpretation of the damping process.

Expanding Eq. (1) for weak damping ($k_i^2 \ll k_r^2$) and $\nu=0$, we have

$$\begin{aligned}&[(ck_r/\omega)^2-1](\sqrt{2}\omega v_T/\omega_p^2)k_r=\mathrm{Re}[Z(\zeta_r)]\,,\\ &[3(ck_r/\omega)^2-1](\sqrt{2}\omega v_T/\omega_p^2)k_i=\mathrm{Im}[Z(\zeta_r)]\,,\end{aligned} \qquad (2)$$

where $\zeta_r=u/\sqrt{2}v_T$, and the cyclotron-resonance velocity $u=(\omega-\omega_c)/k_r$. From Eq. (2) for slow phase velocity ($c^2k_r^2/\omega^2 \gg 1$), we find an expression for the damping rate as

$$k_i/k_r=\tfrac{1}{3}\mathrm{Im}[Z(\zeta_r)]/\mathrm{Re}[Z(\zeta_r)]\,. \qquad (3)$$

Evidently, the damping rate is governed by ζ_r, i.e., the ratio of cyclotron-resonance velocity to thermal velocity. By analogy with Landau damping for longitudinal waves, this means that the damping rate is determined by the slope of the velocity distribution function at the cyclotron-resonance velocity.[9]

The experiment is performed in a discharge plasma[10] produced in argon at a pressure of 5–10×10^{-4} Torr with an oxide-coated cathode of 10-cm diameter [see Fig. 1(a)]. Experimental parameters are carefully arranged to satisfy the following Olson's criteria.[2] Provided (i) $(\omega_p/\omega_c)^2c/v_T \gg 1$ and (ii) $k_ic/\omega_c \lesssim 1$, the cyclotron-damped response (the least-damped pole) is dominant for (iii) $z \gtrsim c/\omega_c$, where z is the distance from the exciter. In addition (iv) the collisional damping should be negligible, and (v) the magnetic field should be sufficiently uniform. Our experimental parameters are the plasma density $n_0=1-3\times10^{12}$ cm^{-3}, $\kappa T_e=2-3$ eV, and the magnetic field $B_0=900-1000$ G; typically $\omega_p/\omega_c\simeq4$, $c/v_T\simeq300$ and $c/\omega_c\simeq2$ cm. Therefore, the first three

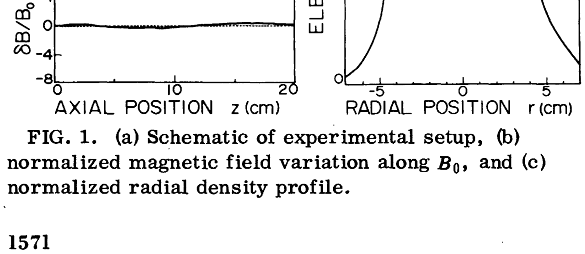

FIG. 1. (a) Schematic of experimental setup, (b) normalized magnetic field variation along B_0, and (c) normalized radial density profile.

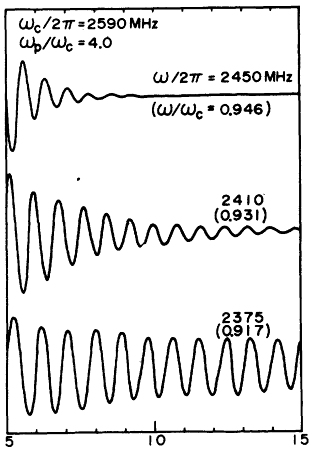

FIG. 2. Typical wave patterns of RHCP waves for different frequencies. The distance z is measured from the exciter.

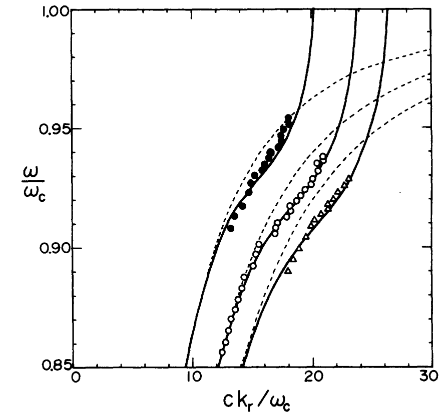

FIG. 3. Normalized frequency versus normalized wave number. Closed circles, open circles, and triangles show the experimental results for (B_0 = 924 G, $n_0 = 1.3\times10^{12}$ cm^{-3}), (980 G, 2.4×10^{12} cm^{-3}), and (943 G, 3.0×10^{12} cm^{-3}), respectively. Solid and dashed lines indicate hot-plasma and cold-plasma dispersion, respectively.

criteria suggest that the least-damped pole term should be measurable for $z \gtrsim 2$ cm. The total collision frequency with electron-electron and electron-neutral collisions included is $\nu/\omega_c = 10^{-4}$–10^{-3}, and hence the collisional effect is negligible (the fourth criterion). Numerical calculations show that the fifth criterion requires the magnetic variation $\delta B/B_0 \lesssim 6\times10^{-3}$. Figure 1(b) shows that the measured spatial variation is $\delta B/B_0 \lesssim 10^{-3}$. The temporal stability ($\delta B/B_0 \lesssim 10^{-3}$) also is attained by driving external solenoidal coils with a transistor-regulated power supply.

Besides Olson's criteria, the recent experiment[10] has shown that the wave refraction effect due to the density inhomogeneity significantly modifies the effective damping along B_0. To exclude this effect, great care is devoted to the density uniformity. The plasma column is substantially uniform over 8 cm in diameter [Fig. 1(c)] and 100 cm in length.

Microwaves of frequency $\omega/2\pi = 2350$–2700 MHz are applied to an exciter antenna (an electrostatically shielded loop of 1.3-cm diameter) in the center of the plasma column. A similar loop antenna which is moved axially along B_0 is used as the detector. Both loops are oriented to pick up only transverse magnetic fields. Interferometer techniques are used to measure the spatial amplitude and phase variations of waves. All data are sampled with a boxcar integrator and averaged over many discharge periods.

Figure 2 shows typical raw data of the axial interferometer traces of the RHCP waves. We omitted the region near the exciter where free-streaming or branch-cut terms are dominant.[2] Also, the geometric divergence of waves from the small source appears near the exciter. Two-dimensional measurements of the wave phase and amplitude profiles have confirmed good approximations of parallel propagation of plane waves for $z \gtrsim 5$ cm. Further, the one-dimensional propagation is justified by another type of excitation, in which the wave is launched from a large plane exciter (open-waveguide antenna[10]) placed at the plasma end [Fig. 1(a)]. The wave patterns in this large plane excitation coincide with those in the small loop excitation for $z \gtrsim 5$ cm. The polarization of the waves has been confirmed, by rotating the exciter loop, in a customary manner.

When the frequency is changed for constant

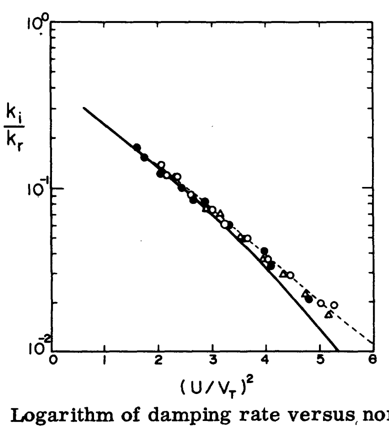

FIG. 4. Logarithm of damping rate versus normalized cyclotron-resonance velocity squared. Experimental points as pair of data in Fig. 3. Solid and dashed line indicate the pure cyclotron damping ($\nu = 0$) and the damping with weak collisions ($\nu/\omega_c = 6\times10^{-4}$), respectively.

magnetic field B_0 and plasma density n_0, the corresponding wavelength is derived from the axial interferometer trace. In this way, the real part of the dispersion relation is measured and plotted in Fig. 3 for three different combinations of B_0 and n_0. Dashed lines indicate the cold-plasma dispersion relation $(ck/\omega)^2 = 1 + \omega_p^2/[\omega(\omega_c - \omega)]$. Solid lines indicate Eq. (1) for $\nu = 0$, where the electron temperature ($\kappa T_e = 2.5$ eV) measured with the Langmuir probe is used. Experimental points agree with the hot-plasma theory very well.

For $\omega/\omega_c \lesssim 0.9$, the waves propagate nearly undamped. With increasing frequency, the wave attenuation is recognized as shown in Fig. 2. It should be noted that a slight increase in the frequency (e.g., $\Delta\omega/\omega_c \simeq 1.5\%$) gives rise to considerable attenuation as $\omega/\omega_c \rightarrow 1$. The damping length k_i^{-1} is determined from the slope in the semilogarithmic plot of the wave amplitude against distance z. Instead of illustrating k_i vs ω/ω_c, the damping rate is plotted as a function of the cyclotron-resonance velocity $u = (\omega - \omega_c)/k_r$, as shown in Fig. 4.

The solid line in Fig. 4 indicates the collisionless damping calculated from Eq. (3). This approximate solution has been confirmed to agree with the exact solutions [Eq. (1) for $\nu = 0$] very well. The effect of weak collisions ($\nu/\omega_c = 6 \times 10^{-4}$ expected in the experiment) is demonstrated by the dashed line, which is derived from Eq. (1) directly. The measured damping for $(u/v_T)^2 \lesssim 3$ is described by the collisionless damping very well, while the weak collisional effect is apparent for larger value of $(u/v_T)^2$. It is remarkable that the experimental points obtained for three different combinations of B_0 and n_0 lie on only one curve in Fig. 4. Thus, the experiment has explicitly verified characteristics of wave-particle interactions in a magnetized plasma, that is, the damping rate determined by u/v_T.

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