Measurement of Collisionless Electron-Cyclotron Damping along a Weak Magnetic Beach*

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We present measurements of collisionless spatial cyclotron damping rates and finite minimum wavelengths near resonance. The plasma density and temperature are determined from wavelength data by solving the hot-plasma dispersion relation far away from and near cyclotron resonance. Damping rates determined from resulting plasma parameters agree with the experimentally determined damping rates as well as with those obtained from Langmuir-probe data.

Electron-cyclotron damping of a right-hand circularly polarized (RHCP) wave is a fundamental process in plasma heating. However, Olson[1] has pointed out that it has not yet been quantitatively measured and compared with hot-plasma theory in the collisionless regime. He has set forth criteria for accurate measurement of spatial cyclotron damping. Lisitano, Fontanesi, and Bernabei[2] have measured the propagation of a RHCP wave along a magnetic beach and compared their results with cold-plasma theory. They experimentally measured the wave number for the range $0.5<\omega/\omega_c<0.8$ and showed that a good correspondence with plane-wave theory is obtained for plasma wavelengths less than the transverse dimension of the plasma column.

In this experiment, a RHCP wave is propagated in a plasma column along a weak magnetic beach under appropriate conditions for the measurement of collisionless electron-cyclotron damping. The wavelengths are measured for $0.7\leq\omega/\omega_c\leq 1.0$, and we observed finite (nonzero) minimum wavelengths near resonance due to thermal effects. The corresponding damping rates are measured for $0.9<\omega/\omega_c<1.0$ for a given α/c and ω_p/ω $[\alpha=(2\kappa T_e/m_e)^{1/2}]$. Experimental results are compared with the linearized hot-plasma plane-wave theory for a RHCP wave propagating parallel to a uniform magnetic field.

The theoretical analysis of the linear spatial damping and dispersion of a RHCP wave propagating parallel to a magnetostatic field has been carried out by Olson.[1,3] He assumed an unbounded plasma, immobile ions, a Maxwellian electron distribution, and a uniform magnetostatic field. He found that the cyclotron-damped response (the least-damped pole) is dominant for $z>c/\omega_c$ provided $(\omega_p/\omega_c)^2c/\alpha\gg 1$, where z is the distance from the source of excitation. The experimental parameters for our plasma are $\omega_p/\omega_c>1$, $\omega_c\gtrsim 1.3\times10^{10}$ rad/sec, and $T_e<25$ eV ($\alpha<3\times10^6$ m/sec). Consequently, $(\omega_p/\omega_c)^2c/\alpha\gtrsim 100\gg 1$ and $c/\omega_c\lesssim 2$ cm. Therefore, the least-damped pole term is dominant for $z\gtrsim 2$ cm and should be measurable in this region.

The least-damped pole response is determined by solving the dispersion relation of the RHCP wave for complex wave number and real frequency:

$$k^2c^2=\omega^2+(\omega_p{}^2\omega/k\alpha)Z_+(\zeta_e), \tag{1}$$

where $\zeta_e=(\omega-\omega_c+i\nu)/k\alpha$, ν is an appropriate collision frequency for the Krook model,[4] and $Z_+(\zeta_e)$ is the plasma dispersion function.[5] Calculating $Z_+(\zeta_e)$ numerically, the dispersion can be solved for $\mathrm{Im}(kc/\omega_c)$ as a function of ω/ω_c with ω_p, α, and ν as parameters. Using an electron-electron collision frequency defined by[6]

$$\nu_{ee}=(2.9\times10^{-6}n\ \mathrm{cm}^{-3})(\ln\Lambda)[T_e(\mathrm{ev})]^{-3/2},$$

it is found that for our experimental parameters $\nu/\omega_c\leq 10^{-4}$, and the effect of collisions can be neglected in Eq. (1). This conclusion agrees with that of Olson[1] for the parameters of our experiment. The other parameters determining $\mathrm{Im}(kc/\omega_c)$ as a function of ω/ω_c can be obtained from the frequency dependence of the wavelength ($\mathrm{Re}kc/\omega_c$). Below resonance such that $|\zeta_e|\gtrsim 3$, $Z_+(\zeta_e)\simeq -1/\zeta_e$. In this limit, the dispersion relation is temperature independent and can be solved for ω_p:

$$\omega_p=\omega_c\{[\mathrm{Re}(kc/\omega_c)]^2-(\omega/\omega_c)^2\}^{1/2}\times(\omega/\omega_c-1)^{1/2}. \tag{2}$$

At resonance, with $\omega\approx\omega_c$, $Z_+(\zeta_e)\simeq -2\zeta_e+i\pi^{1/2}$. The dispersion relation can be solved for α, using the value of ω_p determined from Eq. (2):

$$\alpha=\left(\frac{2\kappa T_e}{m}\right)^{1/2}=\frac{1.15\omega_p{}^2c}{\omega_c{}^2[\mathrm{Re}(kc/\omega_c)]^3}. \tag{3}$$

From Eqs. (2) and (3), α and ω_p are determined

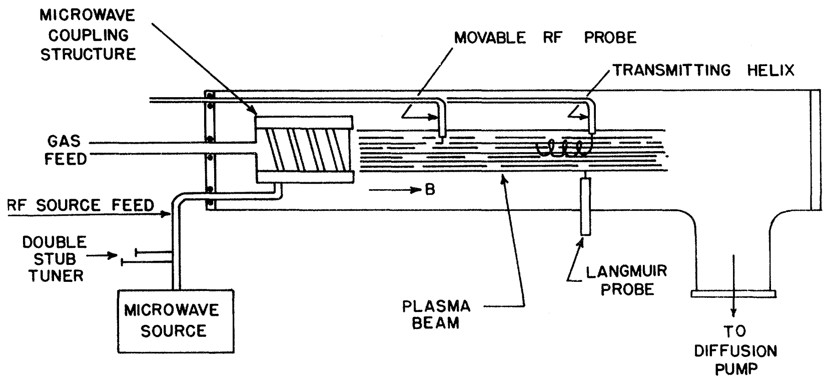

FIG. 1. Plasma wave facility.

by experimentally measuring wavelengths (Rekc/ω_{ce}) for $\omega \approx \omega_{ce}$ and ω below resonance such that $|\zeta_e| \gtrsim 3$. Using these plasma parameters, theoretical damping rates (Imkc/ω_c) can be calculated from the dispersion relation [Eq. (1)] and compared with experimental results.

Shown in Fig. 1 is the experimental apparatus. The plasma is created by a Lisitano coil using argon and helium gases at pressures of 10^{-3} to 5×10^{-6} Torr with a base pressure of 2×10^{-7} Torr. The Lisitano coil is fed by microwave power levels of 10 to 100 W at 2.445 GHz corresponding to a resonance at $B_0 = 875$ G inside the source. The electron densities are 5×10^{10} to 1×10^{12} electrons/cm^3 and temperatures of 4 to 25 eV. Densities and temperatures were measured from wave propagation data, and when compared with Langmuir-probe measurements were found to agree within 20% for the electron temperature and within a factor of 2 higher for density measurements.

The Lisitano coil is placed half-way between the midplane and the mirror point in a magnetic-mirror machine. A vacuum-bounded plasma column 50 cm long and 5 cm in diameter is produced. Axial and radial density variations were measured and found to be less than 10% over the column. Wave measurements are performed on the opposite side of the magnetic mirror. The transmitting antenna is a 2-cm-diam helix formed by the thin center conductor of a semirigid coaxial transmission line which is completely immersed inside the plasma column of 5 cm diam. The helix couples well to the plasma when it is located in a magnetic field substantially above resonance ($\omega_c > 1.5\omega$), and when the density is sufficiently high so that $\omega_p/\omega > 1$.

Both small coaxial rf probes and electrostatically shielded loop antennas which can be moved axially along the plasma column or rotated about its axis were used as receiving antennas. When the loop was oriented to pick up only transverse magnetic fields, an increase in received signal strength above that for a rf probe was obtained with an interferometer curve and cutoff similar to that obtained with the rf probe. This confirmed the transverse electromagnetic nature of the wave being studied.

To check the sense of polarization of the wave, a comparison of the phase shifts introduced by rotation and translation of the loop relative to the static magnetic field was made. This confirmed that polarization was in the sense of electron rotation about the magnetic field. The wave power was measured by a superheterodyne detector and found to be nearly constant as the loop was rotated, confirming the circular polarization of the wave. Radial profiles of the wave amplitude are broad bell-shaped curves, decreasing rapidly at the column edge. The magnetic field variation is known to within $\pm 0.1\%$, and its absolute magnitude to within $\pm 0.5\%$.

A phase-sensitive homodyne wave-detection system was used to measure the real part of the dispersion relation. The voltage output of the system is proportional to

$$V_n(z) \sim e^{-(\mathrm{Im}k)z} \cos[(\mathrm{Re}k)z + \varphi], \tag{4}$$

where φ is an adjustable reference phase of the system. A plot of $V_n(z)$ versus z on an X-Y recorder enables measurement of average values of Rek over a half-wavelength centered at the peak of the half-wavelength to be computed for four or five values of ω/ω_c for $0.6 < \omega/\omega_c < 1.0$. Changing φ allows the average of Rek to be computed at different values of ω/ω_c without changing the position of the transmitting antenna. Thus, the real part of the dispersion relation

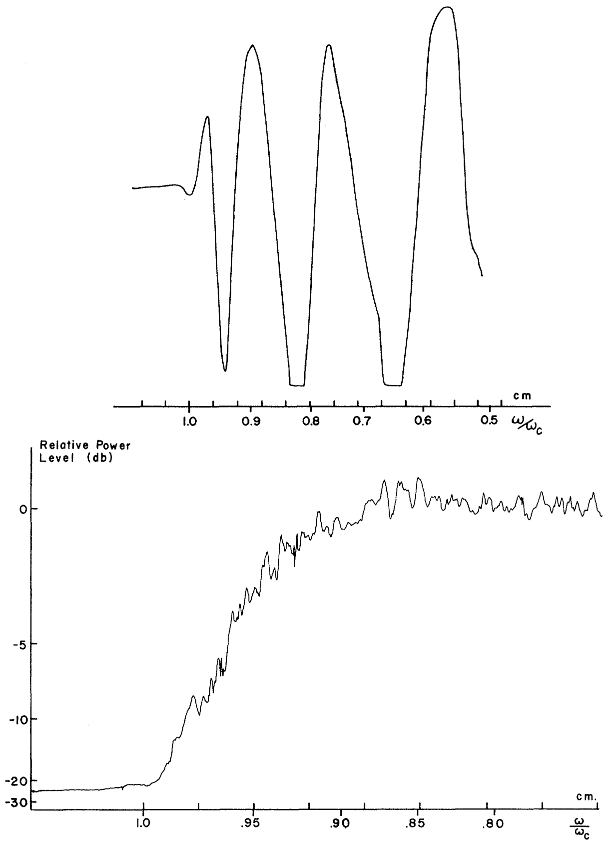

FIG. 2. (a) Phase-sensitive homodyne detection output; $\omega_p/\omega = 1.82$, $T_e = 8.4$ eV, and $f = 2.06$ GHz. (b) Superheterodyne detector output; $\omega_p/\omega = 1.37$, $T_e = 7.9$ eV, and $f = 1.95$ GHz.

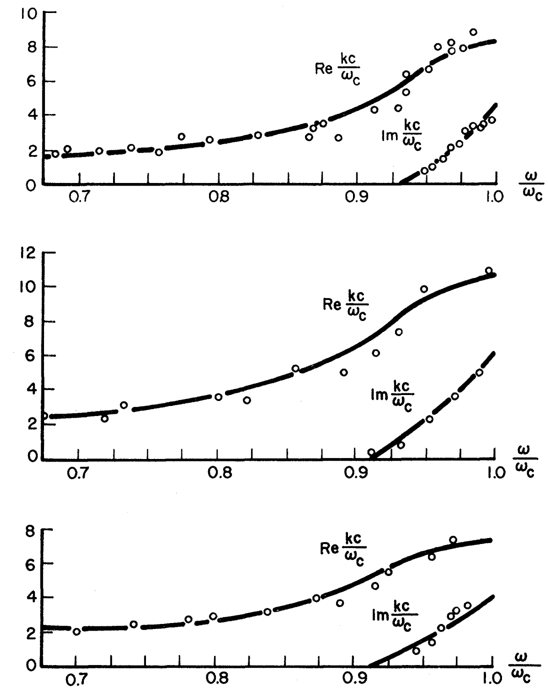

FIG. 3. Experimentally measured dispersion and damping curves. (a) $\omega_p/\omega = 1.5$, $T_e = 5.2$ EV, and $f = 1.95$ GHz. (b) $\omega_p/\omega = 2.3$, $T_e = 6.3$ eV, and $f = 2.2$ GHz. (c) $\omega_p/\omega = 1.7$, $T_e = 17$ eV, and $f = 1.95$ GHz.

can be experimentally measured for all ω/ω_c between 0.6 and 1.0.

The damping rate (Imk) was measured using a superheterodyne detection system whose output is proportional to

$$|E(z,t)| \sim V_s(z) \sim e^{-(\mathrm{Im}k)z}. \qquad (5)$$

Imk can be measured with a plot of $V_s(z)$ versus z on an X-Y recorder. Using a superheterodyne detector also enables one to see if there are standing wave patterns along the magnetic beach caused by too strong a magnetic field gradient which causes partial reflection of the wave.

Shown in Fig. 2(a) is an interferometer trace of the phase-sensitive homodyne detection system. Also shown is a centimeter scale and the variation of the magnetic field along the beach. Wavelengths ranging from 5 to 1 cm are observed. Since the diameter of the plasma is 5 cm, plane-wave theory for an unbounded plasma should be applicable, especially near resonance where the wavelengths are the shortest and where damping rates are measured.[2] Shown in Fig. 2(b) is the voltage output of the superheterodyne detector. The magnetic field variation is shown together with a centimeter scale. Small fluctuations on the voltage output are due to probe motion on the microwave discharge. The smooth variation of the voltage output indicates that reflected power along the magnetic beach is small.

Shown in Fig. 3(a) are the experimental results of the dispersion relation for a plasma for which $\omega_p/\omega = 1.5$ and $T_e = 5.2$ eV. The theoretical curves shown are determined by these values. Argon gas was used at a pressure of 5×10^{-5} Torr with 40 W power. The experimental points for each interferometer trace are shown on the real part of the dispersion relation. Average values of many damping measurement runs are shown on the Im(kc/ω_c) curve. Error bars on this curve are as much as 3 circles in total height. Good correspondence with theoretical results is evident.

Shown in Fig. 3(b) are the experimental results of the dispersion relation for a plasma for which $\omega_p/\omega = 2.3$ and $T_e = 6.3$ eV. Argon gas was used at a pressure of 1×10^{-4} Torr with 50 W power. The difference in temperature between Figs. 3(a) and 3(b) has little effect on the $\mathrm{Im}(kc/\omega_c)$ curves. Therefore, Figs. 3(a) and 3(b) show the effect of increasing ω_p/ω on the damping rates. The whole $\mathrm{Im}(kc/\omega_c)$ curve is raised without altering its slope with increasing ω_p/ω, as predicted by theory. $\mathrm{Re}(kc/\omega_c)$ is also raised for increased ω_p/ω. The minimum wavelength for $\omega/\omega_c \lesssim 1.0$ is shorter for the higher-density case.

Shown in Fig. 3(c) are the experimental results of the dispersion relation for a plasma where $\omega_p/\omega = 1.7$ and $T_e = 17$ eV. Helium gas was used at a pressure of 1×10^{-4} Torr with 100 W power. Comparing Fig. 3(c) with Fig. 3(a) shows the effect of increased temperature on the dispersion relation. The $\mathrm{Im}(kc/\omega_c)$ slope is much less in this case, and damping rates become significant further away from resonance. The $\mathrm{Re}(kc/\omega_c)$ curve is also much flatter, and the minimum wavelength for $\omega/\omega_c < 1.0$ is longer for the higher-temperature case.

The conditions for accurate measurement of collisionless cyclotron damping have been shown to be well satisfied for our experimental parameters. We have presented a technique for determining the plasma density and temperature from wavelength data near and far from resonance, and shown that the camping rates determined from them are consistent with both the measured damping rates and the values determined from Langmuir-probe curves. From this, one concludes that the use of the hot-plasma theory for unbounded plasmas is sufficient to describe wave damping and dispersion properties near resonance when wavelengths are smaller than the plasma column diameter and the magnetic beach is sufficiently weak.

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Rayleigh Disk in dc Helium II Counterflow*

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The torque on a Rayleigh disk in dc helium II counterflow produced by a heater has been measured over the range 0.969 K to T_λ. We find that the response of the disk is approximately the same for normal fluid and superfluid. A torque deficit of $\approx 50\%$ of that from potential-flow theory appears to be explainable in terms of turbulent, supercritical flow in the channel, rather than anomalous disk behavior. These findings are in contradiction to a number of other studies involving net mass flow relating to the "λ-point anomaly" of Pellam.

Recently, Trela[1] suggested a theory of helium II flow which is consistent with his measurements of torque on a Rayleigh disk in a nonrotating system and also reproduces some of the features of the "λ-point anomaly" of Pellam[2] (especially in view of the later work by Lynch and Pellam[3]).

We have made measurements of the torque on a Rayleigh disk in another nonrotating system, helium II counterflow produced by a heater (presumably the dc analog of earlier second-sound resonance investigations[4,5]). Figure 1 is a scale drawing of the apparatus; measurements were also made on several Pyrex prototypes which are generically similar to Fig. 1.[6] The device consists basically of a square-cross-section flow channel (area 0.991 cm^2) with a 19 Ω/□ resistor-board heater at the sealed end. A 0.016-cm-thick Au-plated disk of diameter $2a = 0.275$ cm, with a 2.54-cm length of 0.0254-cm-diameter 99.999%-pure Cu rod attached, was suspended from a quartz fiber (≈ 5 μm in diameter). The fiber constant was 0.653×10^{-3} dyn cm. An external magnet (≈ 700 G) was used for eddy-current damping. The device was made of machined Lucite pieces, glued together with Weldon No. 3.[7]

The theoretical response of the device can be