LANDAU DAMPING OF LOW AND HIGH
POWER SLOW ELECTROSTATIC WAVES

BY

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LANDAU DAMPING OF LOW AND HIGH POWER
SLOW ELECTROSTATIC WAVES

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ABSTRACT

We have excited waves in a warm plasma at frequencies above the lower hybrid frequency and have measured their damping characteristics under a variety of conditions. Strong wave absorption was measured if $\omega/k_{\parallel} \lesssim 3 v_e$, in agreement with the predictions of linear Landau damping. At a certain critical power level, consistent with the power required to flatten the velocity distribution, the absorption disappears. Above this level we have obtained evidence for the appearance of an enhanced electron tail between 80 - 250 eV, in and above the energy range where Landau damping should occur.

A number of methods of heating hot plasmas in toroidal fusion reactors have been proposed, including the application of radio frequency power near the lower hybrid frequency. Experiments have demonstrated that lower hybrid waves can be excited in plasmas by means of phased waveguide arrays¹ or loops,² that they propagate in well defined resonance cones,³ and that under certain conditions they undergo strong absorption.⁴ While the coupling and propagation characteristics of lower hybrid waves are now fairly well understood, few of the possible damping mechanisms are understood in detail.

Aside from possible nonlinear absorption processes such as parametric decay, lower hybrid waves may also be damped by means of linear processes, such as collisions, linear mode conversion, and Landau damping. Porkolab and Bellan,² for example, have shown that collisions tend to obscure linear mode conversion in low temperature plasmas. In hot fusion plasmas, however, electron collisions will not function as an effective absorber, but Landau damping of the slow electrostatic waves may be quite effective.⁵⁻⁸ In this process the radio frequency power is absorbed by electrons travelling along the field lines at a velocity close to the parallel phase velocity of the waves. It has been recognized that an upper limit to the power transfer to the electrons is set by a flattening of the electron velocity distribution, which reduces the rate of absorption. This redistribution, predicted by quasilinear theory,⁹ is opposed by electron collisions, which tend to reestablish a normal distribution.

Absorption of slow electrostatic waves has been observed in linear test devices and has been attributed to linear Landau damping by non-thermal electrons in an energetic tail.⁴ In this paper we report measurements at a low power level of wave damping consistent with Landau damping by the main body of electrons and disappearance of the damping at higher power levels.

The experiment was performed on the linear H-1 device,¹⁰ which produces a helium plasma 2 m long and 10 cm in diameter, confined by a 10 kG magnetic field. The plasma is generated by a 7 kW high frequency (155 MHz) field pulsed 50 times a second. Measurements are performed in the afterglow during a time interval in which the central density remains constant at $n_e \approx 7 \times 10^{10} \text{ cm}^{-3}$, but the electron temperature falls from ~ 7 to 1 eV. Thus in these experiments we are able to vary the parameter $\alpha = \omega/k_{\parallel} v_e$, which determines the rate of wave absorption,¹¹ by pulsing the waves at selected times.

Azimuthally symmetric waves of frequency between 50 and 120 MHz and duration 3 μ s were excited by an electrostatic antenna positioned on the liner surrounding the plasma. The exciter consisted of a 20 cm long array of 9 evenly spaced rings of diameter 9.5 cm. Even numbered plates were energized alternately out of phase by an external circuit, while odd numbered plates were held at machine potential. The antenna generates parallel wavelengths of about 8 cm with a full half width of $\Delta\lambda/\lambda \sim 0.5$. For other measurements, a ring antenna producing a broad range of wavelengths around 18 cm was also used.

The antenna generates a resonance cone of electrostatic waves, the amplitude and trajectory of which may be calculated by matching the WKB solutions inside the plasma with the exact solutions of the wave equation near the plasma boundary.^{3,12} In the interior of the plasma, where $\omega_{pe}^2 \gg \omega^2 \gg \omega_{pi}^2$ and $\omega^2 \ll \omega_{ci}\omega_{ce}$, the wave potential is given by

$$\phi(r, z) = \beta \{r \operatorname{Re}[Q(r)]\}^{-1/2} \int_{-\infty}^{\infty} dk_{\parallel} \frac{S(k_{\parallel})}{|k_{\parallel}|^{2/3}} \exp i k_{\parallel} [z + \int_{r_0}^r Q(r') dr'] , \quad (1)$$

where $Q(r) = (-\epsilon_{\parallel}/\epsilon_{\perp})^{1/2} \sim (\omega_{pe}/\omega) [1 - i\nu/2\omega - i\sqrt{\pi}\alpha^3 \exp(-\alpha^3)]$. The antenna spectrum $S(k_{\parallel})$ is assumed to have negligible components in the parallel wavelength range where the electrostatic approximation in the plasma interior is invalid. Here r_0 is the radius of the critical density and β is a geometrical constant. A characteristic feature of linear Landau damping is that the wave absorption is large only when $\alpha \sim 3$ where Q has an appreciable imaginary component.

We have been unable to measure directly the wavelength spectrum of the waves because of density fluctuations in the plasma column. However, with the aid of two probes placed in the resonance cone we have found that the group velocity at 70 MHz ($\sim \omega/k_{\parallel}$) is $\sim 6 \times 10^8$ cm/sec and is consistent with the calculated peak of the $k_{\parallel}$ spectrum.

Figure 1 shows the observed radial amplitude ($P < 1$ watt) for 70 MHz waves at various distances from the antenna. In the two cases, the plasma densities are identical but the electron temperatures, also included in the figure, are different. The peak of the wave packets follow the resonance cone trajectory calculated for the experimental density profile. This agreement

shows that we have indeed excited the slow electrostatic mode, for which the dispersion relation is $\omega = \omega_{pe} k_{||}/k$. In the hotter plasma, the wave packet is observed to be heavily damped. We attribute this attenuation to the linear Landau damping process since the parameter $\alpha \sim 3$ for $T_e = 7$ eV and strong interaction is expected.

In Fig. 2 we show a comparison of the measured and calculated wave amplitude at various axial distances from the end of the antenna. The wave amplitude is taken to be the spatially averaged signal level (proportional to ϕ^2) over the plasma cross section, or $\int_0^a \phi^2 dA$. The solid curves show the theoretical predictions using the measured temperature and density profiles, and the points give the experimental data. We obtain the best fit if the central temperature is ~ 7 eV, which is consistent with the probe measurements of Fig. 1. The results at this frequency are therefore in good agreement with linear Landau damping theory. Data taken at other frequencies (90 - 120 MHz) show qualitative agreement with theory, i.e., the absorption rate decreases with frequency but not as rapidly as predicted by Eq. (1). This feature could be caused perhaps by the existence of a small electron tail or by a shift in the radiated antenna spectrum not accounted for in the theory. Similar results have been obtained with the longer wavelength antenna and as expected, reduced attenuation was observed at all frequencies.

Collisional wave absorption is much too weak to explain the observed attenuation when the electron temperature is 7 eV. Electron-ion collisions are negligible and the electron-atom mean free path is ~ 1 meter. In addition, the collision rate between electrons and helium atoms¹³ is

approximately constant in the 1-7 eV temperature interval ($\nu \sim 10^6 \text{ sec}^{-1}$) and therefore cannot account for either the magnitude or temperature dependence of the absorption. When the electron temperature has relaxed to 1 eV, however, the observed amplitude decrease is determined by collisional damping and by wavelength and geometric effects as shown in Fig. 2.

The measured attenuation lengths are independent of the applied power up to a certain critical level, above which the absorption disappears. Data in Fig. 3 indicate a critical power level of ~ 25 watts. We believe that this effect is not caused by a depletion of the plasma density in the region of the resonance cone, because Langmuir probes show no significant expulsion of electrons from this region. Rather, the evidence points strongly to a flattening of the electron velocity distribution. This has been measured directly by a Langmuir probe which showed an apparent increase in the electron "temperature" of 15-20 eV.

One can estimate the power P required to flatten the electron distribution function $f(E)$ in a time T by

$$P \approx \frac{1}{T} [n^*(E_2 - E_1) - \int_{E_1}^{E_2} E f(E) dE] ,$$

where T is the average time an electron spends in the resonance cone, $f(E)$ is the Maxwellian energy distribution function and n^* is the number density of electrons in the flat portion of the distribution function which is determined from particle conservation. E_1 and E_2 are the minimum and maximum energies at which electrons interact strongly with the waves and are

determined principally by the spectrum excited by the antenna but also by trapping phenomena,¹⁴ which increases the width of the energy interaction interval. For the short wavelength antenna with 20 cm long interaction distance, we estimate P to be in the range 5 - 20 watts. Collisions produce negligible drag on the fast electron tail in our case but in toroidal plasmas they may determine the slope of the energy plateau.

Direct evidence for the RF interaction with the electron tail has been obtained from a four-element electrostatic analyzer placed at the end of the column. Some results are shown in Fig. 4. At high power (1 kW), an electron tail develops between 80 and 250 eV, which is the expected energy range for our antennas. The amplitude of the tail signal depends on the applied power, but the saturation point and the shape are invariants, depending only on the antenna geometry. The interpretation of these data is that, in the highly nonlinear limit, many tail electrons are swept up to higher energies by resonant RF electric fields.

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Fig. 1. Resonance cones at successive axial distances from the antenna for two electron temperature profiles. The central plasma density is $7 \times 10^{10} \text{ cm}^{-3}$, magnetic field 10 kG and frequency 70 MHz.

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Fig. 2. The amplitude of the probe signal at 70 MHz versus axial distance from the antenna. The solid curves are theoretical results for various central electron temperatures. Curve (b) is for a 1 eV plasma while curve (a) has no damping.

Fig. 3. The damping length at 70 MHz versus input wave power. The measurements were taken when the central electron temperature was 7 eV.

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Fig. 4. The collected electron current of the energy analyzer versus retarding grid potential. The input wave power is 1 kW at 70 MHz, and results are given for both short and long wavelength antennas.