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RELATIVISTIC EFFECTS ON CYCLOTRON WAVE ABSORPTION BY AN ENERGETIC ELECTRON TAIL IN THE PLT TOKAMAK

By

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Relativistic Effects on Cyclotron Wave Absorption by an Energetic Electron Tail in the PLT Tokamak

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Abstract

Electron cyclotron wave absorption by mildly relativistic electrons in the low density regime of the PLT tokamak is investigated. Appreciable wave damping is found for vertical propagation at frequencies of 50, 60, and 70 GHz when the spatially constant cyclotron frequency is 89 GHz. The perpendicular temperature $T_\perp(v_\parallel)$ of the fast tail is also measured from emission of radiation in the same direction. The results obtained are in satisfactory agreement with the theory of wave emission and absorption.

Several authors have pointed out the importance of the relativistic mass variation in the theory of electron cyclotron resonant absorption. It is found that for wave propagation normal to the magnetic field, the absorption and the resulting electron heating are entirely determined by the relativistic resonance equation $(p/mc)^2 = (\omega_c/\omega)^2 - 1$, where p is the electron momentum, c is the speed of light, m is the electron rest mass, and ω and ω_c are the wave and the electron cyclotron frequencies, respectively. For thermal plasmas with temperatures of a few keV, $(p/mc)^2 \simeq T_e/mc^2 \simeq (2\text{-}4) \times 10^{-3}$, and $\Delta\omega/\omega \simeq (1\text{-}2) \times 10^{-3}$ is too small for an accurate investigation of the relativistic frequency down-shift of the absorbed (emitted) radiation. A tokamak plasma, in addition to the dense thermal component, often possesses a small population of energetic electrons with momentum $p \simeq mc$. This energetic tail, which occurs in low density ohmic discharges or during lower hybrid current drive experiments,[1,2] is well-suited for an accurate experimental verification of relativistic effects on wave absorption.

In this Letter, we present the first experimental investigation of the absorption of an electron cyclotron wave with frequency $\omega \ll \omega_c$ in a low density ($< 10^{13}$ cm^{-3}) ohmic PLT discharge. We used wave propagation in the vertical direction where ω_c is spatially constant and wave absorption is highly selective in the electron momentum space.

A narrow beam of microwaves was launched into the PLT torus along the vertical direction intersecting the center of a poloidal cross section. For both the launching and the receiving antennae we used an open C-band waveguide with the longest side perpendicular to the toroidal magnetic field. In order to find the true plasma absorption, the measured values were corrected for the spurious contributions of refraction. In the case of our geometry, the effect of refraction caused by a symmetric electron density profile on a wave propagating in the ordinary mode is the same as that of a divergent cylindrical lens. On the contrary, because of the 1/R dependence of the toroidal magnetic field, the refractive effects on a wave propagating in the extraordinary mode are, for $\omega >> \omega_p$, those of a prism that bends the ray trajectories towards the lower magnetic field side. For a parabolic density profile with a central density of 5×10^{12} cm^{-3} and a toroidal magnetic field of 32 kG, a narrow wave beam with a frequency of 70 GHz has its divergency increased by a factor of 1.3, if in the ordinary mode of propagation, and its wave vector bent by 5° if in the extraordinary mode. For the antennae used in our experiment, this means that refraction by itself causes a reduction of the transmitted signal by 20 and 90 percent, respectively. Because of this large refraction effect on the propagation of the extraordinary mode, we limited our investigation mostly to the absorption of the ordinary mode. Nevertheless, preliminary results obtained with the extraordinary mode are consistent with those obtained with the ordinary mode.

In Fig. 1, the time evolution of the transmitted signal is shown for the case of $\omega/2\pi$ = 60 GHz and a toroidal magnetic field of 32 kG (ω/ω_c = 0.67). The line average density $\bar{n}$ had a constant value of 2.5×10^{12} cm^{-3} from t = 300 msec up to the end of the discharge while the plasma electrical current climbed from 400 kA to 500 kA. During this phase, the value of $\tau = \ln(I_o/I)$ (where I and I_o are the beam intensities received with and without plasma, respectively) was 1.7. This value had to be lowered to 1.4 to take into account the effects of refraction. Absorption measurements were carried out at three different frequencies. Some of the results are shown in Fig. 2 for the case of a plasma with $\bar{n} = 3 \times 10^{12}$ cm^{-3}.

We found that the plasma absorption of waves with $\omega << \omega_c$ disappears for $\bar{n}$ approaching a value close to 1×10^{13} cm^{-3}.

We have also measured the radiation temperature T_r in the range of frequencies $0.7 < \omega/\omega_c < 0.9$ with an absolutely calibrated heterodyne receiver. The emission measurements were made in the vertical direction by using the receiving antenna of the transmission setup. The results are shown in Fig. 3 for $\bar{n} = 3 \times 10^{12}$ cm^{-3}. Since the absorption measurements indicate that the electron beam is only partially optically thick, the measured values of T_r are affected by reflections at the tokamak boundaries. We assume that the effect of boundary reflections is to raise the level of radiation to the blackbody value and therefore T_r is a good estimate of the perpendicular temperature of fast electron . Note that the low range of measured frequencies is below the minimum electron cyclotron frequency in the PLT plasma. Again we found that T_r for values of $\omega << \omega_c$ dropped significantly as $\bar{n}$ approached 1×10^{13} cm^{-3}.

In order to model the experimental results, we describe the tail distribution by $F(p_\parallel, p_\perp) = n_b f_\parallel(p_\perp)\ f_\parallel(p_\perp, p_\parallel)$ where $n_b << \bar{n}$, $f_\parallel(p_\parallel)$ is the parallel distribution and $f_\perp$ is the perpendicular distribution for a given value of $p_\parallel$. As shown by the experimental results, the radiation temperature has a sharp rise for large values of $\omega_c - \omega$. The emitted radiation is then produced by electrons with $p \approx mc$ and, therefore, it is legitimate to assume that the perpendicular temperature of the emitting and absorbing electrons has a sharp rise near the far end of the tail, i.e., for $p_\parallel \approx p_b \approx mc$. Let $\Delta p_\parallel = p_2 - p_1$ be the range of the parallel momentum of the hottest part of the tail and $\Delta p_\parallel/2 << p_b = (p_1 + p_2)/2$. One can show that,[3] as far as emission and absorption of electron cyclotron radiation is concerned, the group of electrons with $p_1 < p_\parallel < p_2$ behaves like an isolated system with $f_\parallel(p_\parallel) = \delta(p_\parallel - p_b)$, and for the absorption coefficients of the two modes of propagation one obtains

$$\tau_o = - 2r_b \frac{2\pi^2 \omega_{pb}^2 \omega_c (mc)^2}{N_o \omega^2 c} S_1 p_b^2 \left(\frac{J_1^2}{p_{\perp b}} \frac{\partial f_\perp}{\partial p_{\perp b}}\right) \quad , \qquad (1)$$

$$\tau_e = - 2r_b \frac{2\pi^2 \omega^2_{pb} \omega_c (mc)^2}{N_e \omega^2 c} S_1 (J_1' - i \frac{\varepsilon_{12} J_1}{\varepsilon_{11} \xi}) p_{\perp b} \frac{\partial f_\perp}{\partial p_{\perp b}} \quad , \qquad (2)$$

where $\omega^2_{pb} = 4\pi e^2 n_b/m$, $p^2_{\perp b} = mc^2[(\omega_c/\omega)^2 - 1 - (p_b/mc)^2]$, $J_1 = J_1(\xi)$ is the Bessel function,

$$\xi = (N_{o,e}\ \omega/\omega_c)(p_{\perp b}/mc) \quad , \quad \varepsilon_{11} = 1 - (\omega_p/\omega)^2/(1 - (\frac{\omega_c}{\omega})^2) \quad ,$$

$$\varepsilon_{12} = i\ (\omega_c/\omega)\ (\omega_p/\omega)^2/(1 - (\omega_c/\omega)^2) \quad ,$$

r_b is the radius of the energetic beam of electrons, $N_{o,e}$ is the refractive index of the ordinary and extraordinary modes, $f_\perp = f_\perp(p_{\perp b}, p_b)$, and $S_1 = (1/2) + p_{\perp b}^2/2|p_{\perp b}|^2$ is the step function which states that $\tau_o = \tau_e = 0$ for $(\omega_c/\omega)^2 < 1 + (p_b/mc)^2$.

The curve in Fig. 2 is obtained from Eq. (1) for $f_\perp$ a Maxwellian with temperature $T_\perp(p_b) \simeq 0.19\ mc^2$ for $p_b/mc = 0.9$, $n_b = 1.1 \times 10^{11}\ cm^{-3}$, and $r_b = 15$ cm. The experimental point at $\omega/\omega_c = 0.78$ lies above the theoretical curve. This is expected because Eq. (1) holds for $T_\perp(p_\parallel < p_1) \ll T_\perp(p_b)$. In the present experiment the transition between the two regions is much smoother than in the theoretical model and the value of τ in the high frequency side is greater than the calculated one.

The electron tail carries an appreciable part of the plasma current, most of which is to be ascribed to the fastest electrons with $v_\parallel \approx c$. For the case under investigation we find I_b = 250 kA to be compared with the total current of 450 kA.

In conclusion, we have produced the first experimental evidence of electron cyclotron absorption at large relativistic frequency shifts. We have investigated the case of perpendicular propagation for $\omega << \omega_c$ but the method can be easily extended to oblique propagation and to higher harmonics. Our results show that wave transmission in the vertical direction is a potentially powerful method for investigating the energetic electron distribution during current drive or low density regimes in tokamak plasmas. This is of interest for understanding the tail formation and the efficiency of current generation for relativistic electrons.[4,5] Furthermore, the disappearance of the fast tail at high density is a crucial point in the method of rf-current drive. For efficient current generation, it is essential to sustain the energetic part of the tail. Our results support the use of the existing gyrotrons at f = 60 GHz to transfer wave energy to the energetic electrons in tokamak plasmas with B_o = 32 kG. This is applicable[6] to plasmas of higher density ($\bar{n} > 10^{13}$ cm^{-3}) than considered in this paper because such plasmas are accessible to the extraordinary mode.

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FIGURE CAPTIONS

FIG. 1. Time evolution of the intensity of a wave with $\omega/2\pi$ = 60 GHz transmitted through a plasma with $\bar{n} = 2.5 \times 10^{12}$ cm^{-3} and $\omega_c/2\pi$ = 89 GHz.

FIG. 2. Experimental values of τ at frequencies of 50, 60, and 70 GHz in a plasma with $\bar{n} = 3.0 \times 10^{12}$ cm^{-3} and $\omega_c/2\pi$ = 89 GHz. The continuous curve is from the theoretical model of Eq. (1).

FIG. 3. Radiation temperature versus ω/ω_c.

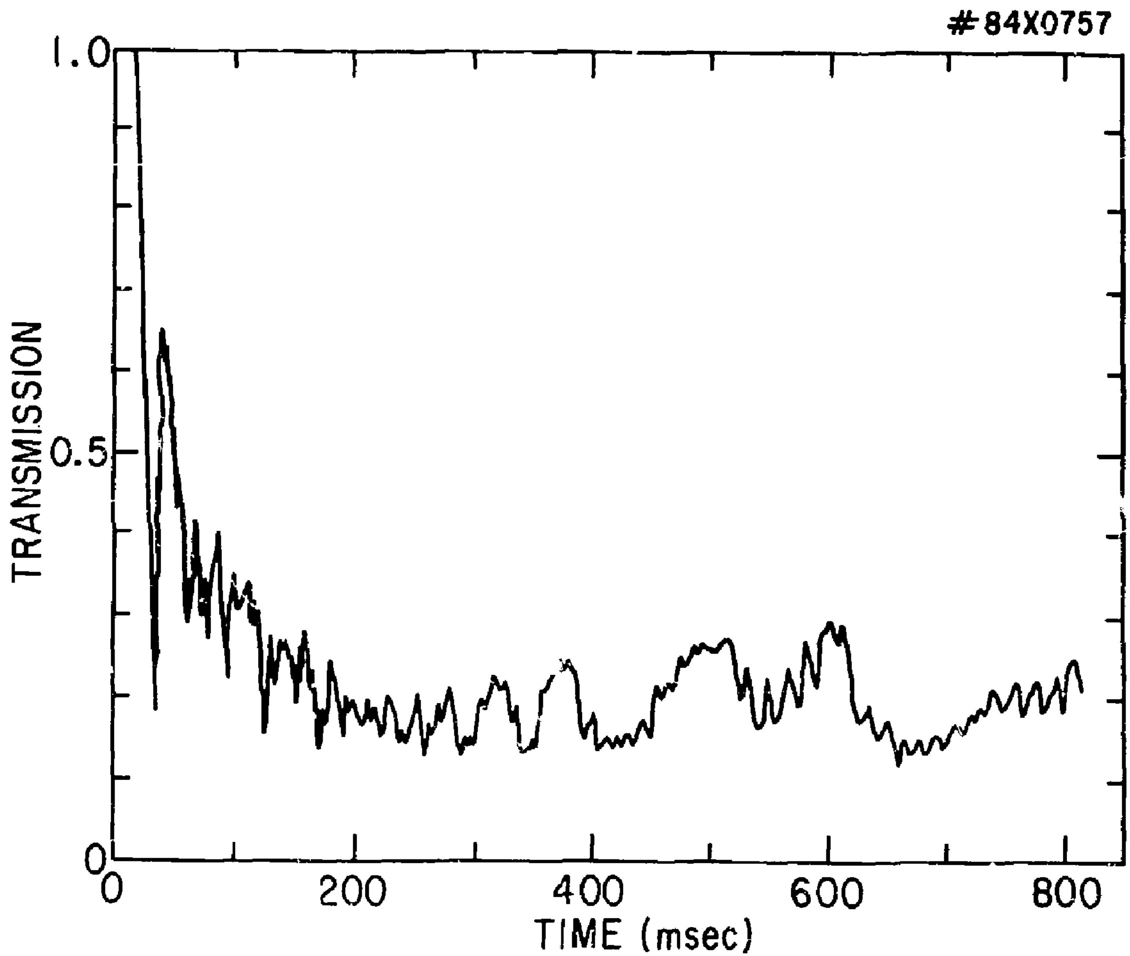


FIG. 1

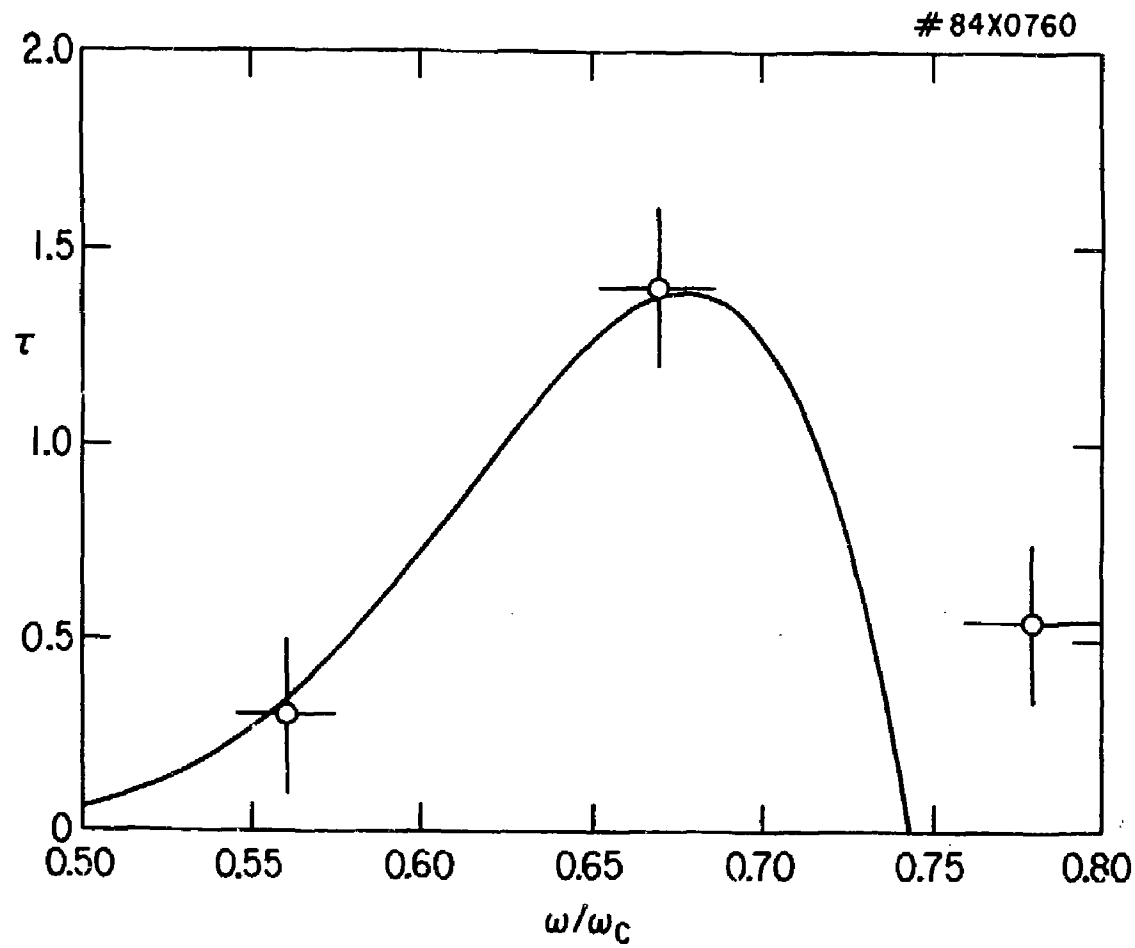
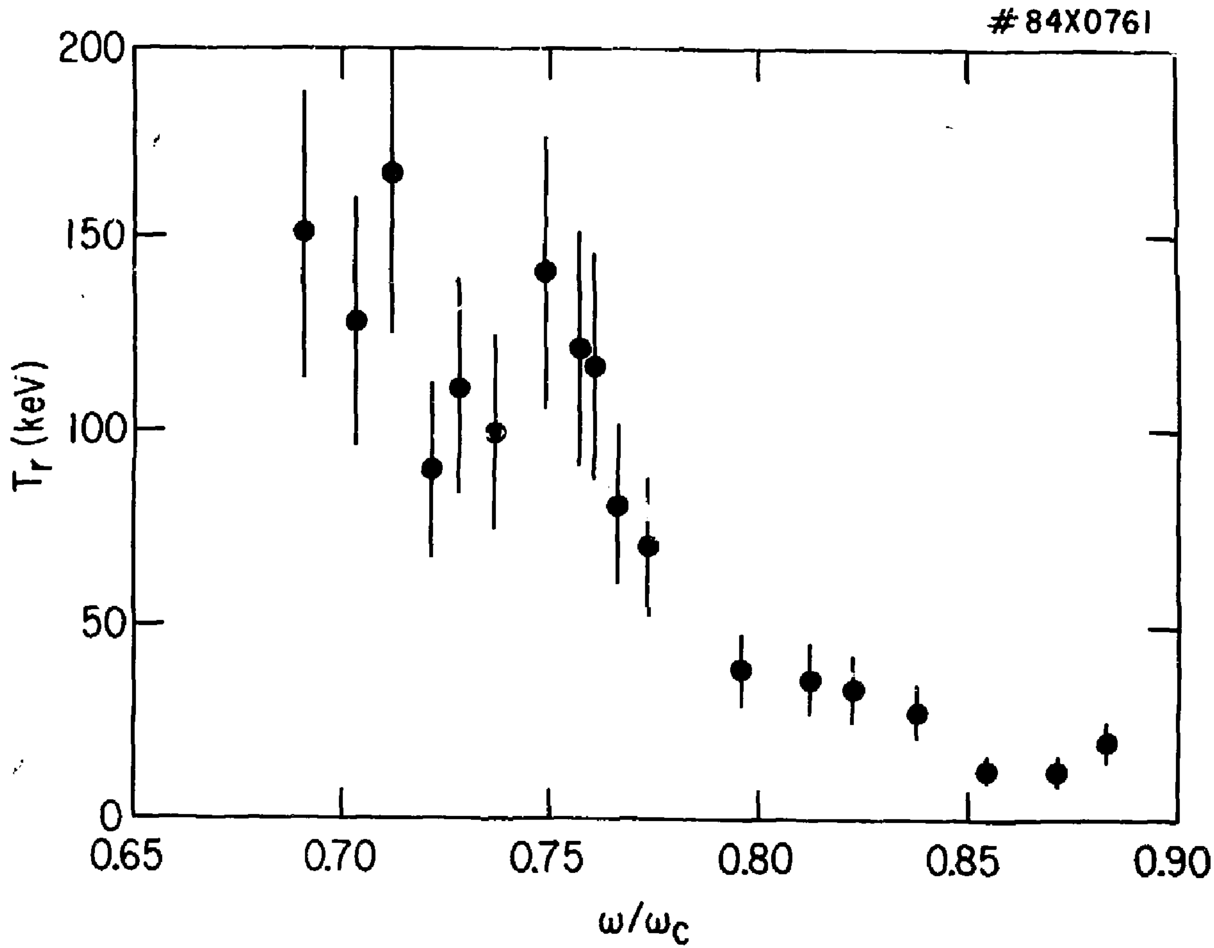


FIG. 2



84X0761
200
150
100
50
0
T_r (keV)
0.65
0.70
0.75
0.80
0.85
0.90
ω/ω_c

FIG. 3

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