1. Publication Nº	2. Version	3. Date	5. Distribution
INPE-4385-PRE/1205		*Sept. 1987*	☐ Internal ☒ External ☐ Restricted
4. Origin *LAP*	Program *PTOR*		

6. Key words - selected by the author(s)

ELECTRON CYCLOTRON WAVES
SUPERTHERMAL ELECTRON VELOCITY DISTRIBUTIONS

7. U.D.C.: *533.9*

8. Title *INPE-4385-PRE/1205*

ABSORPTION OF ELECTRON CYCLOTRON WAVES BY SUPERTHERMAL ELECTRON VELOCITY DISTRIBUTIONS IN TOKAMAK PLASMAS

10. Nº of pages: *7*

11. Last page: *6*

12. Revised by

Ludwig

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Director General

14. Abstract/Notes

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15. Remarks

Published in the Proceedings of the Course and Workshop on applications of RF waves to tokamak plasmas, Varenna, Italy (Monotypia Franchi, Perugia, 1985), Vol. 2, p. 770.

ABSORPTION OF ELECTRON CYCLOTRON WAVES BY SUPERTHERMAL ELECTRON VELOCITY DISTRIBUTIONS IN TOKAMAK PLASMAS

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Abstract

We consider a tokamak plasma in which the distribution of electron velocities in the direction parallel to the magnetic field has a monotonically decreasing superthermal tail. A fully three-dimensional ray-tracing code is used to calculate the absorption of the extraordinary mode in the nonrelativistic limit. The results indicate that small tails (tail fraction < 0.5%) can significantly affect wave absorption at low densities. In a high-density plasma where the extraordinary mode cutoff is present, tail electrons can cause substantial absorption. The use of a gyrotron with frequency much less than the central electron cyclotron frequency with an outside launch position is found to be very effective in the presence of tail electrons.

There is now considerable experimental evidence for the occurrence of extended superthermal tails in the distribution of electron velocities parallel to the magnetic field in a wide range of tokamak plasmas [1,2]. Such tails represent a low-density, high-temperature component of the plasma which is predicted [3-6] to be a particularly good absorber of radiation in the electron cyclotron range of frequencies. It is accordingly of interest to include a tail component in a ray-tracing treatment of electron cyclotron resonance heating (ECRH) in tokamak plasmas. Here, we have represented a superthermal tail by adding a nonrelativistic drifted Maxwellian distribution (parallel drift velocity v_D, temperature T_T), which contains a small fraction μ of the electrons, to a bulk Maxwellian distribution (thermal velocity v_e) which contains the remaining fraction $1-\mu$ of the electrons. The fraction μ remains the same at all points within the plasma. The parameters μ, v_D, and T_T are chosen subject to the constraints that the tail is monotonically decreasing and compatible with observed plasma current values, soft X-ray spectra, and existing numerical models. Our nonrelativistic approach is valid for the X-mode away from normal incidence, which is the only case considered here. This representation of the distribution function gives rise to simple analytic expressions [7] for the dielectric tensor elements. These are employed in a fully three-dimensional ray-tracing code [7], using realistic tokamak geometry, antenna patterns, and spatial profiles for the plasma parameters. We have studied the effect of a wide range of tail formations on the power deposition profiles and integrated absorption during ECRH; a more detailed discussion of the results outlined here is given in Ref. 7. It should be noted that the variation of a single tail parameter produces a wide range of physical effects. For example, as v_D increases, the number of electrons with high $v_\parallel$ increases, a plateau region begins to form, and the Doppler-shifted cyclotron resonance moves outwards into regions of the plasma where density and temperature are lower. In the numerical approach employed here, we obtain an accurate and realistic description of the combined effect on absorption of these contrasting physical changes.

We have chosen plasma parameters which are characteristic of a medium-size tokamak. For radiation of frequency $\omega/2\pi = 60$ GHz and a central electron number density $n_e(0) < 8\times10^{19}$ m^{-3}, the X-mode has no high-density cutoff and the fundamental cyclotron resonance $\omega = \Omega_e(0)$ is accessible. It follows from the nonrelativistic resonance condition $\omega = k_\parallel v_\parallel + \Omega_e(x)$ that for a high-field side launch with $k_\parallel < 0$, the radiation interacts first with tail electrons. This is shown in Figs. 1a-c, where the deposition of a substantial proportion $\approx 35\%$ of the incident energy among high-velocity electrons away from the centre of the plasma is shown for typical tail parameters ($\mu = 5\times10^{-3}$, $v_D = 3v_e$, $T_T = 13.5$ keV, corresponding to $I_p \approx 200$ kA at this density). We have found that for μ as low as 10^{-3}, approximately 10% of the incident power is absorbed in the tail; this rises to 60% for $\mu = 10^{-2}$, and approaches 100% for $\mu = 5\times10^{-2}$. The integrated absorption increases with v_D, but falls as T_T increases. We conclude that in this low-density regime, very small tails have a disproportionately large effect on the absorption of electron cyclotron radiation by the plasma.

For $n_e(0) > 8\times10^{19}$ m^{-3}, the X-mode has a high density cutoff, so that the rays are strongly refracted away from the centre of the plasma and the cyclotron resonance of the bulk thermal electron distribution is inaccessible. For high field side launch with $k_\parallel < 0$, energetic tail electrons in the outer region of the plasma which is traversed by the waves may undergo resonant heating (Fig. 2a). For typical tail parameters ($\mu = 5\times10^{-3}$, $v_D = 4.5v_e$, T_T= 13.5 keV, corresponding to $I_p \approx$ 1 MA at this high density), power deposition is localised near the edge of the plasma and is due exclusively to the tail electrons (Fig. 2b); 38% of the incident radiation is absorbed in this way. Our results show that significant power deposition can occur in high-density plasmas where the X-mode cutoff is present, provided that the electron velocity distribution has a superthermal parallel tail with $\mu > 5\times10^{-3}$ and that the tail electrons are physically present in the outer regions of the plasma. This suggests that the presence of a small tail should be examined further as a possible explanation for the recent experimental results on Doublet-III [8] and FT-1 [9], where significant absorption was observed for densities above the X-mode cutoff. In these experiments, the launch angle was well away from the perpendicular, so that the current drive mechanism may have led to the production of tail electrons. We note that in this regime, the wave energy is deposited exclusively among the high-$v_\parallel$ tail electrons, which are the most efficient targets for current drive.

We have also applied our ray tracing code for ECRH in the presence of a superthermal electron tail to a heating and current drive scenario proposed by Fidone and co-workers [3,10]. Suppose that the gyrotron source has a frequency $\omega << \Omega_e(0)$, so that the resonance $\omega = \Omega_e(x)$ lies outside the torus. In this case, radiation launched from the low-field side with $k_\parallel < 0$ can resonate with high-$v_\parallel$ electrons which satisfy the condition $v_\parallel = \left(\omega - \Omega_e(x)\right)/k_\parallel$. Again, heating is confined to the superthermal electrons, which is advantageous for current drive. In addition, the possibility of using a relatively low-frequency gyrotron source and the launch position on the outside of the torus are both attractive for engineering reasons. The results of the ray-tracing calculations for a typical set of tail parameters ($\mu = 5\times10^{-3}$, v_D = $3v_e$, T_T = 13.5 keV) are shown in Figs. 3a,b. The power is deposited uniformly around the centre of the plasma, which is probably advantageous for plasma stability. The absorption profile in velocity space peaks at the tail, and 70% of the incident power is deposited in the plasma. This figure is remarkably high, given the small value of μ. The strong absorption is due in part to the fact that in this launch configuration, the right circularly polarised component of the wave at the centre of the plasma is substantially greater than in the conventional X-mode fundamental heating regime. This effect diminishes as the bulk plasma density increases, and this is reflected in our results. We find that both the integrated absorption and the width of the resonance region in velocity space increase with v_D. For a very small tail with $\mu = 10^{-3}$, integrated absorption is 20%, and this rises to 100% for $\mu = 5\times10^{-2}$. The integrated absorption is also sensitive to launch angle; for the typical tail parameters listed above, it is 70% for $\theta = 120°$ and 100% for $\theta = 135°$.

We conclude firstly that even small superthermal electron tails can absorb a large fraction $\gtrsim$ 30% of the incident X-mode power in a low-density plasma; this fraction approaches 100% for $\mu = 5\times10^{-2}$. Secondly, we have shown that small tails can absorb significant amounts of radiation in high-density plasmas where the X-mode cutoff shields the cyclotron resonance of the bulk thermal electrons. Thirdly, we have considered the case of a low-frequency source, $\omega \ll \Omega_e(0)$, for which the cyclotron resonance lies outside the torus. Here, a small tail can absorb upwards of 80% of the incident X-mode radiation which is launched from the outside of the torus, and absorption remains high for a wide range of parameter values. Heating is concentrated on the tail electrons, as in the previous case, and this is advantageous for current drive. Finally, we remark that small tails have a disproportionately large effect on the absorption of radiation in the electron cyclotron range of frequencies, both in low-density and in high-density plasmas. We have indicated how some anomalous absorption effects may prove to be explicable in terms of the presence of a monotonically decreasing superthermal electron tail. Conversely, independent information on the extent of such tails will be of use in interpreting experimental absorption data.

Acknowledgement: One of us (A.M.) thanks the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico of Brazil for financial support.

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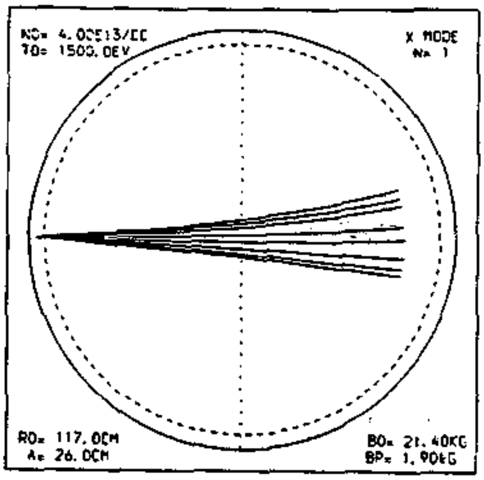
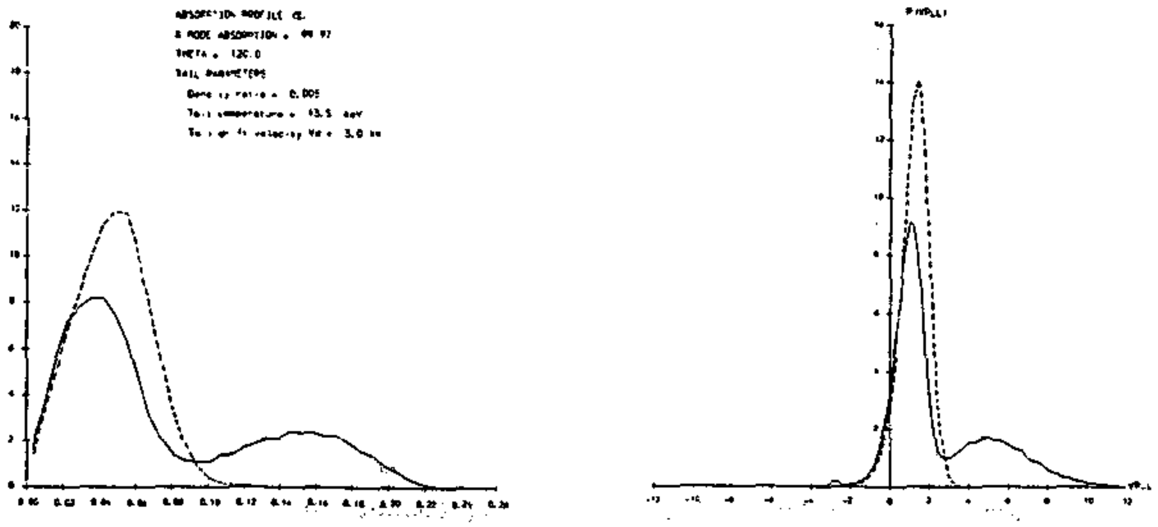


Fig. 1a.
Minor cross section projection of ray trajectories in the presence of a tail. Plasma parameters are displayed. Each cross on a ray marks a 5% decrease in the power carried by the ray. Vertical dashed line marks $\omega = \Omega_e(x)$. Rays terminate at the upper hybrid resonance.



Figs. 1b,c. Power deposited per unit radial coordinate interval (b) and per unit parallel velocity interval (c). The dashed curve shows the result in the absence of a tail.

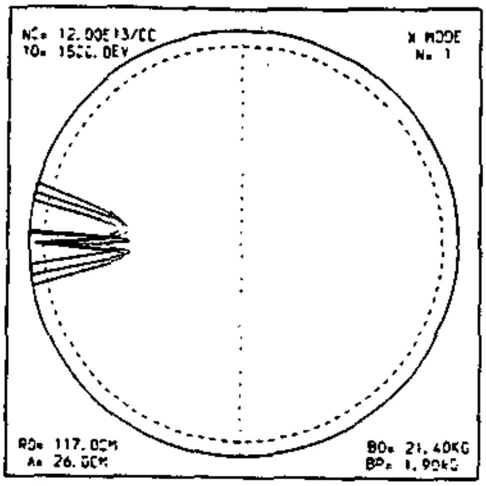


Fig. 2a.
Minor cross section projection of ray trajectories in the presence of a tail for a high density plasma.

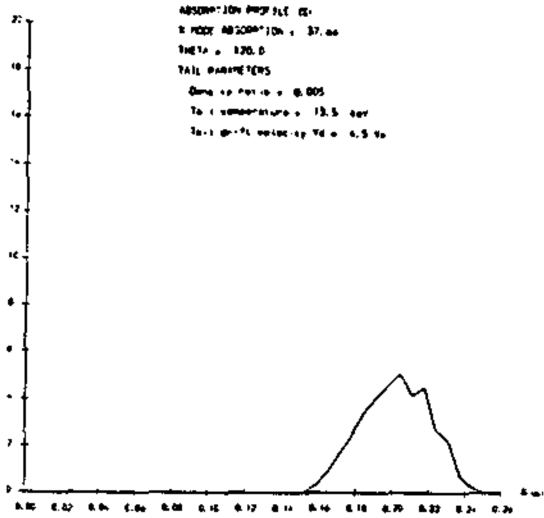


Fig. 2b.
Power deposited per unit radial coordinate interval for the configuration of Fig. 2a.

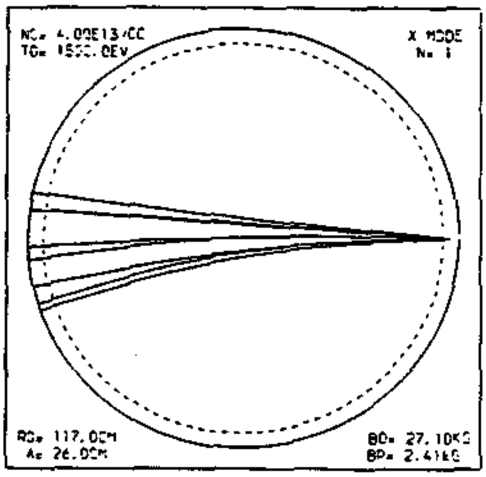


Fig. 3a.
Minor cross section projection of ray trajectories in the presence of a tail for X-mode launch from the outside of the torus with $\omega \ll \Omega_e(0)$ and no cyclotron resonance within the torus.

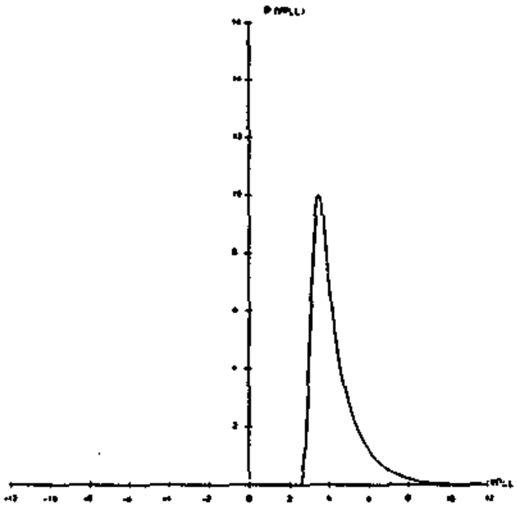


Fig. 3b.
Power deposited per unit parallel velocity interval for the configuration of Fig. 3a.

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TÍTULO

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LIMITE	DEFESA	CURSO	ORGÃO
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NOME DO REVISOR: GERSON OTTO LUDWIG

RECEBIDO	DEVOLVIDO	ASSINATURA
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APROVAÇÃO

NOME DO RESPONSÁVEL: GERSON OTTO LUDWIG

APROVADO	DATA	ASSINATURA
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REV. LINGUAGEM

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Nº DA PUBLICAÇÃO: PÁG.:
CÓPIAS: Nº DISCO: LOCAL:

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- [ ] SIM
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OBSERVAÇÕES E NOTAS

Classificação: PRE

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INPE 106