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Kinetic Effects on Electron Cyclotron Emission during Modulated ECRH in TJ-IU

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Abstract

A multichannel radiometer for second harmonic electron cylotron emission is used to measure the response of the electron temperature to sinusoidal modulation of the RF power, in the range 1–20 kHz. The ECE signals corresponding to the power deposition region show a phase delay in comparison with the modulated power that increases with the modulation frequency from $\phi = 0.4\pi$ to $\phi = 1.6\pi$. This result is inconsistent with standard assumptions of transport theory and hints that finite propagation time of the perturbation through momentum space, as suggested by kinetic theory, has to be taken into account.

Keywords:

electron cyclotron emission, electron cyclotron heating, perturbative transport, kinetic theory

1. Introduction

Modulated ECRH has been used in several experiments to measure the profile of the electron thermal conductivity (see, *e.g.*, Refs. [1-4]). A basic assumption, on which the interpretation of heat-wave propagation experiments rests, is that the energy transferred from the microwaves to the electrons is thermalized instantaneously (*i.e.*, much faster than the energy and particle transport times). Experimental determination of the kinetic relaxation times to validate this hypothesis is not trivial (see Ref. [5]). There are, however, two simple and easily verifiable consequences that follow from this assumption:

i) The phase delay existing between microwave and temperature modulations – at the radial position corresponding to its minimum, *i.e.* at the center of the absorption layer – is a function of the layer width only, varying between two limiting values: $\pi/4$ for narrow layers, and $\pi/2$ for broad layers.
ii) The phase delay is independent of the modulation frequency.

As a consequence, any experimental result showing that the phase delay depends on the modulation frequency, and that delays well in excess of the maximum limit ($\pi/2$) exist contradicts the assumption of instantaneous thermalization of the absorbed energy, which is at the basis of the fluid treatment of transport.

The purpose of this paper is to report measurements showing that this is actually the case, and to suggest that these results can be naturally explained by taking into account the kinetic nature of the absorption process.

2. Experimental Results and Discussion

Modulated ECRH (X-mode, 2nd harmonic, 37 GHz, P = 140–160 kW, pulse duration ≈ 25 ms) experiments have been carried out in the TJ-IU torsatron ($l = 1$, $m = 6$, $R = 0.6$ m, $a \approx 0.1$ m, iota(0) = 0.23) The gyrotron was located at the toroidal angle $\varphi = 30°$ (where $B(0)$ = 0.67 T). A 4-channel heterodyne radiometer, positioned at $\varphi = 0°$, was used to acquire space/time resolved radiative temperature measurements. This system detects the second harmonic

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**Corresponding author's e-mail: luna@ciemat.es* electron cyclotron emission frequency, in the X-mode polarization, from the low-field side of the plasma. By changing the Local Oscillator frequency it is possible to cover all the plasma cross section ($f \approx 43.5$ GHz corresponds to the plasma axis at this toroidal position). To limit wall reflections, the ECE antenna faces an absorber at the opposite wall of the vessel.

For the typical parameters of a TJ-IU discharge (average electron densities below 5×10^{18} m^{-3} and central electron temperatures of the order of 200—300 eV) the plasma is optically grey. In this case a significant population of suprathermal electrons can be generated by ECRH, which causes ECE at downshifted frequencies and distorts the measurements at the low field side of the plasma. An example of the radiative spectra measured with the ECE radiometer is shown in Fig. 1. The radiative spectrum, between 42 and 40 GHz in Figure 1 is entirely determined by the emission of the fast electron population radiating at the downshifted second harmonic frequency. Around 43 GHz some reabsorption by the thermal plasma takes place, and since most suprathermal electrons are located near the plasma axis, also at higher frequencies the radiation temperature is close to the electron temperature. Since the whole plasma is optically grey, the ECE diagnostic is not useful for absolute temperature measurements. However, since both thermal and non-thermal components of the emitted electron cyclotron radiation are measured, it is possible to observe the response of the electron distribution function to a perturbation of the RF power over the whole energy interval being heated by the microwaves.

For the modulated ECRH experiments, the gyrotron power is sinusoidally modulated during 10 ms, with frequencies between 1—20 kHz. The averaged power output was 140 kW, with a peak-to-peak modulation amplitude of 80 kW. Modulation with a single-harmonic component is chosen because, at finite-power levels, the plasma response is expected to be non-linear with the power. The perturbation induced by the modulated heating is clearly seen in the whole ECE spectrum. In the high-frequency part of the ECE spectrum, the modulated emission comes, as well, from suprathermal electrons heated by the fraction of the RF beam propagating through the outer part of the plasma; this has to be contrasted with the corresponding average emission, which comes from nearly thermal electrons: both energy contributions are always present but weigh differently in modulated and steady-state spectra. For the highest modulation frequency (20 kHz), only the ECE signals from the low-frequency channels respond to the perturbation. This can be explained by observing that at this modulation frequency only higher-energy electrons, which are more sensitive to the microwave power, can respond to the power modulation, and this only if the power density is large enough, which is not the case for off-axis electrons (high-frequency channels).

Standard Fourier analysis was performed to obtain the phase delay relative to the applied RF modulation and the amplitude (A) of the oscillations in the ECE signals.

Figure 2 shows the amplitudes of the T_{rad} perturbation for different modulation frequencies. The amplitude of the perturbation decreases with increasing modulation frequency. The amplitudes of the oscillations in the ECE signals are calculated using the raw ECE signals multiplied by a calibration factor; the amplitudes corresponds to those of the Fourier component, that is zero-to-peak values.

Figure 3 shows the phase delay measured ($\Delta\phi/2\pi$) for different modulation frequencies. The phase shift profile is quite flat within all the spectral region and the shift increases for increasing modulation frequency.

The errors bars included in Figs. 2 and 3 are due to scattering of the data points (four reproducible discharge are analysed for each modulation frequency). Equilibrium calculations have shown that for the TJ-IU

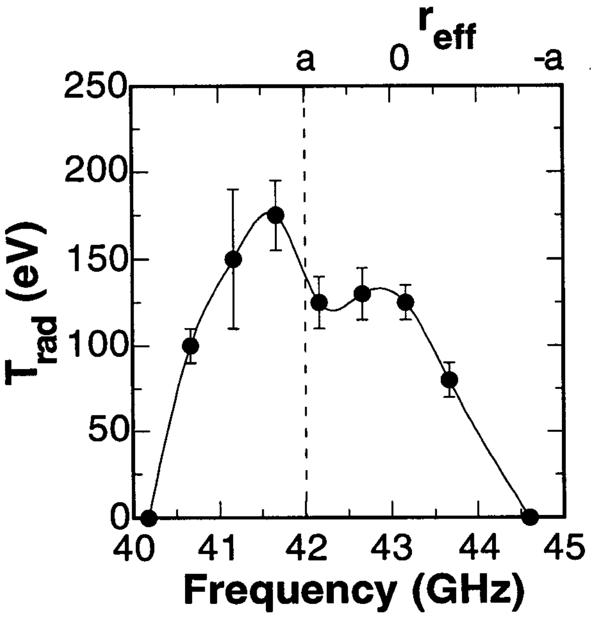

Fig. 1 Radiative temperature measured by the ECE radiometer in TJ-1 U.

plasma parameters the modulation produces a negligible plasma displacement. In the case of the $\Delta T_{\rm rad}$ data, a systematic error could appear due to errors in the calibration procedure. To estimate the corresponding amplitude of the electron temperature perturbation, optical thickness correction should be included in the analysis of the data.

The ECH power deposition profile in TJ-IU consists of a relatively narrow contribution (beam diameter ≈ 4 cm) from the first pass absorption (20% of the injected power predicted by ray tracing calculations) and a broader contribution made up by the power reflected from the inner torus wall after the first pass through the plasma. This is consistent with the flatness of the phase profile and the width of the $\Delta T_{\rm rad}$ profile.

In the framework of standard transport theory, modulated heating is described by a source term in the energy transport equation, with a given spatial profile and with a sinusoidal variation of the amplitude in time. The solution to the energy transport equation shows that the electron temperature is modulated with a phase shift satisfying the two properties given in Sec. 1. The measurements presented in Fig. 3 are in clear disagreement with these properties.

In the framework of kinetic theory, the power absorption is characterized not only by the spatial profile but by the momentum localization as well. The power modulation causes the electron distribution function to oscillate periodically with amplitudes and phase shifts that are functions of the momentum.

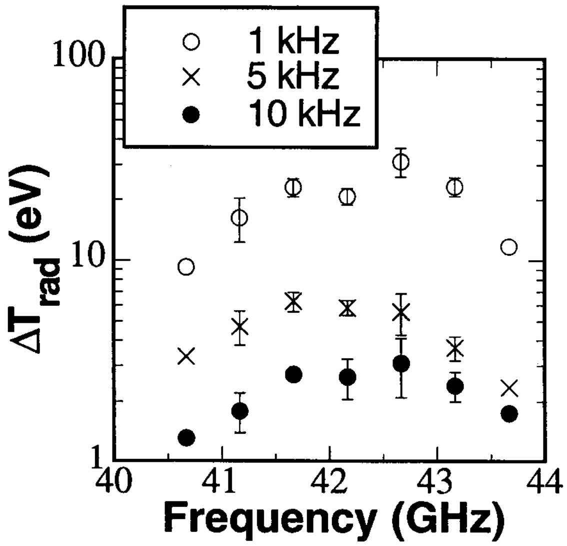

Fig. 2 Amplitude of the radiative temperature perturbation ($\Delta T_{\rm rad}$) for different modulation frequencies.

Some qualitative properties of the oscillations of the distribution function are discussed next, in terms of a simple model kinetic equation (see Ref. [6]), including just two mechanisms that act on the distribution function: collisional drag and diffusion, and quasilinear diffusion. Figure 4 shows the oscillations of the distribution induced by power modulation described by a quasilinear diffusion coefficient with Gaussian shape in momentum, centered at $u = p/p_{\rm th} = 3.9$, with width

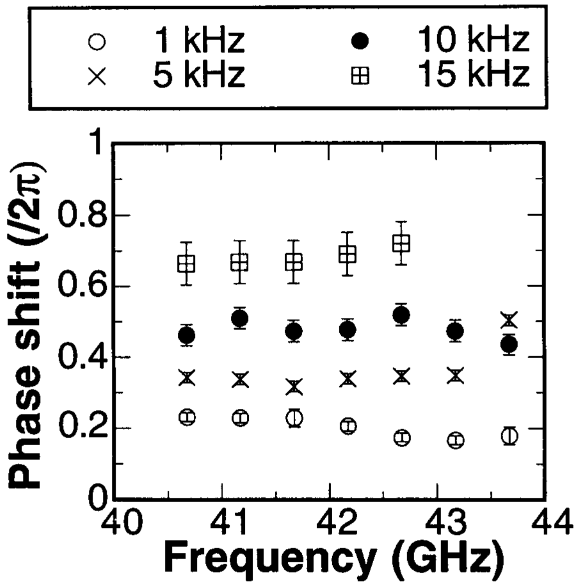

Fig. 3 Measured phase shift of the $T_{\rm rad}$ relative to the modulated RF power for different modulation frequencies.

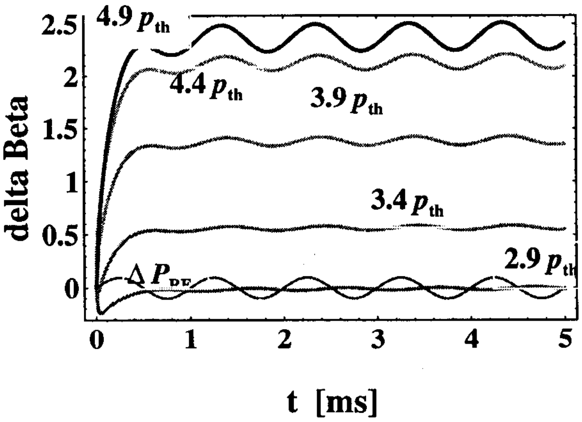

Fig. 4 Computed evolution of the emission coefficient (in A.U.) for different resonant momenta.

$\Delta u = 0.5$, and for 10% amplitude modulation with $f_{\text{mod}} = 1$ kHz. One can observe that the response to the perturbation is more pronounced at higher momenta. Figure 5 shows that the phase shift is a sensitive function of the momentum and an increasing function of the modulation frequency.

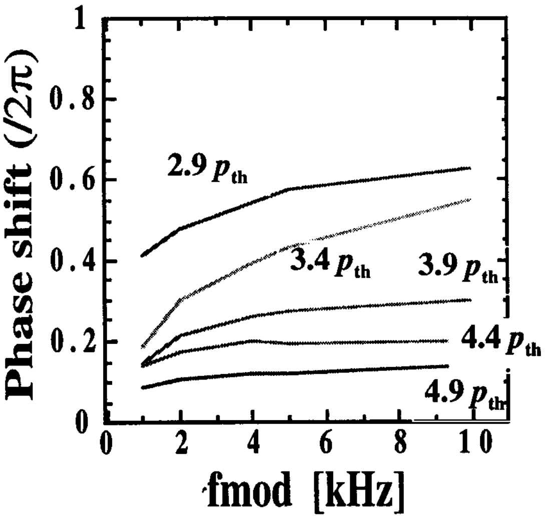

Fig. 5 Computed phase shift of the emission coefficient relative to the modulated power for different momenta.

3. Conclusion

The higher sensitivity of the tail of the distribution to the power modulation, and the strong increase of the phase shift with the modulation frequency exhibited by the kinetic model reproduce qualitatively the experimental findings and point to the kinetic origin of these phenomena.

Power modulation experiments at frequencies of the order of the electron collision frequency, combined with fast diagnostics sensitive to both bulk and tail electrons allow to determine the thermalization rate of the absorbed power, and to ascertain possible incorrectness of simple fluid transport modeling.

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