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Bulk Electron Distribution Function and Corresponding TS and ECE Spectra during ECH

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Introduction

Electron Cyclotron Heating can modify both the electron temperature and current density profiles in a narrow spatial region near the resonance. This capability is useful for the study of transport processes and for the optimization of confinement in plasmas.

While the localization of the power deposition near the resonance is a fundamental property of the wave-particle interaction and is in very good agreement with the experimental findings, the thermalization of the energy absorbed by the electrons is usually deduced on the basis of qualitative arguments and it is difficult to verify experimentally. Typically, two independent values of the electron temperature are obtained by measuring the Thomson Scattering and Electron Cyclotron Emission spectra. Agreement between the TS and ECE temperatures—within the experimental error bars—is considered to proof practically that the electron distribution function is Maxwellian and is characterized by that temperature.

Following this conceptual framework, however, three puzzling sets of results have emerged over the years:

i) Existence of very strong temperature gradients for on-axis heating (earlier findings are reported in Ref. 1, recent results can be found in Ref. 2).

ii) Peaking of the central electron temperature that is related to changes of the magnetic configuration and to the P_{EC}/n_e level observed in W7-AS.[3]

iii) Filamentation of the electron temperature profile observed in RTP by high-resolution TS during—but not only—on-axis ECH.[4]

Some of the conclusions reached on the previous points, and the validity of the thermal equilibrium assumption are challenged by new Fokker-Planck simulations that predict the existence of non-Maxwellian bulk distribution functions during ECH.[5,6]

The novelty of these results has two main reasons. Numerically, it depends on the high resolution achieved by using a parallel solver of the kinetic equation, making possible the use of fine poloidal and spectral grids in the computation of the quasilinear diffusion coefficient. From a formal point of view, the quasilinear term is exactly consistent with the energy and momentum absorption rate obtained from the standard theory of wave damping (i.e., on every magnetic surface, at each poloidal position and for each component of the wave spectrum, rather than in some average sense).

Here we study how TS and ECE temperature measurements are affected by the distortion of the bulk of the electron distribution function, and examine some functional dependence that is related to the width of quasilinear diffusion coefficient in phase-space.

Electron Temperature Profiles

We consider FTU parameters:[2] f = 140 GHz, O-mode polarization, normal injection in the equatorial plane, P_{EC} = 360 kW, $n_e(0)$ = 3.76 10^{13} cm^{-3}, $T_e(0)$ = 5.6 keV, and Z_{eff} = 6.7; the beam waist is 2.5 cm. The computational grids are: $r \times u \times \theta = 16 \times 250 \times 250$, $\chi \times N_{||}$ = 282×127 (where θ is the pitch angle and χ the poloidal angle). The effect of the Ohmic field is neglected. Symmetry of the wave beam with respect to the equatorial plane is assumed, thus doubling the effective poloidal resolution.

The electron distribution function is computed centering the absorption profile at different positions near the plasma axis. This is done by changing the toroidal magnetic field in the range: B_0 = 4.98 - 5.18 T. The width of the parallel spectrum, $\Delta N_{||} = \sin(\Delta\psi)$, is also varied, $\Delta\psi = 1.25^\circ, 2.5^\circ, 5^\circ$, to take into account possible broadening induced by turbulence. The maximum deformation of the distribution function is found at r = 0 when the absorption profile is centered on-axis (for $B_0 \approx$ 5.08) : see Fig. 1 (the labels give the equilibrium momentum; the level curves corresponding to the Maxwellian distribution would be regularly spaced at $\Delta u = 0.25\, u_{th}$ steps). The deformation is not large. However, the temperature of the energy distribution (which is obtained by integrating the distribution function over the pitch-angle) shows that the effect on the slope of the distribution is significant (Fig. 2).

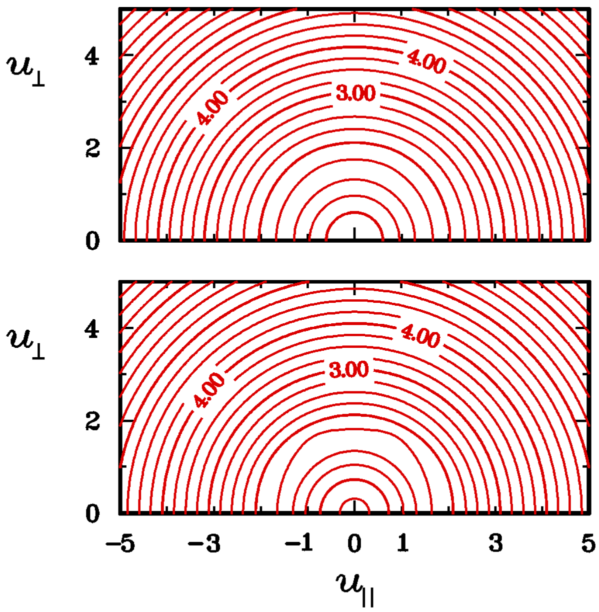

FIG. 1. Top $\Delta\psi = 5^\circ$, bottom $\Delta\psi = 1.25^\circ$.

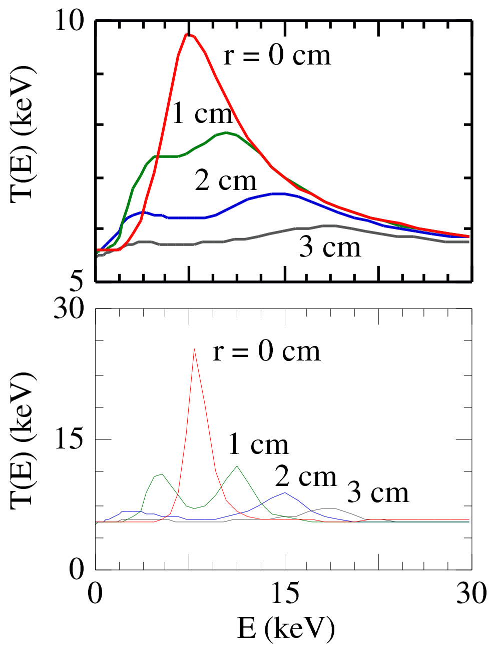

FIG. 2. Top $\Delta\psi = 5^\circ$, bottom $\Delta\psi = 1.25^\circ$.

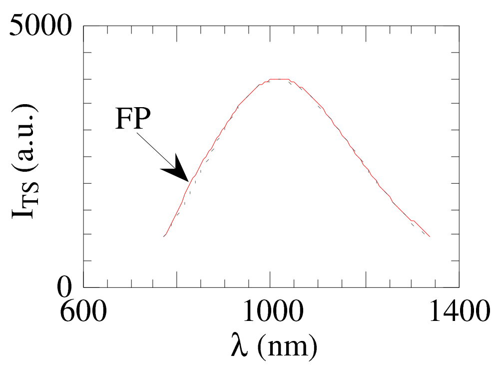

Figure 3 (left) compares the TS spectrum obtained from the FP distribution function (r = 0, $\Delta\psi = 1.25^\circ$) and from a Maxwellian fit. The fit is very good, which shows how misleading can be the mere visual inspection of TS spectra.[4] In fact, the TS temperature is actually well above the Maxwellian value, as shown in Fig. 4; the large error bars are caused by the deviation of the bulk distribution function from the Maxwellian. (The temperature profile is determined by fitting the blue wing of the spectrum.[7])

Figure 5 shows the corresponding ECE temperatures. The sharp central peak is due to the quasilinear flattening of the distribution function: $T_{\rm rad} \propto \beta/\alpha$ (emission/absorption coefficient), and $\alpha \to 0$ for $\Delta N_{\|} \to 0$.[8] Typically, this peak is averaged out because of finite instrumental resolution, and the ECE temperature profile agrees fairly well with the TS one.

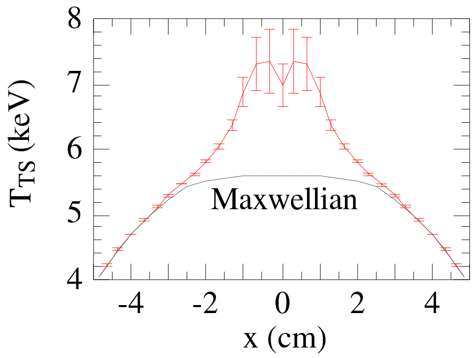

FIG. 4.

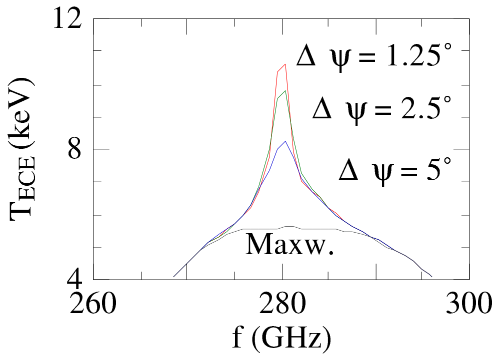

FIG. 5.

The quasilinear deformation of the bulk decreases when shifting the absorption profile slightly off-axis, as shown by the corresponding TS temperature in Fig. 6. The ECE spectra now show twin peaks, the higher being the one located on the side of the power deposition (Fig. 7). The decrease is only in part associated with lower power density at larger radii (20% decrease at $r = 2$ cm). There is also a change induced by the poloidal variation of the magnetic field $\Delta B = B(r, \chi = \pi) - B(r, \chi = 0)$. In fact, both $\Delta N_{\|}$ and ΔB determine the width of the quasilinear term in phase-space: the more localised the quasilinear term, the stronger the quasilinear deformation of the distribution function.

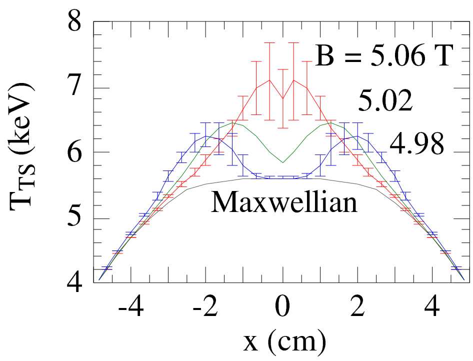

FIG. 6

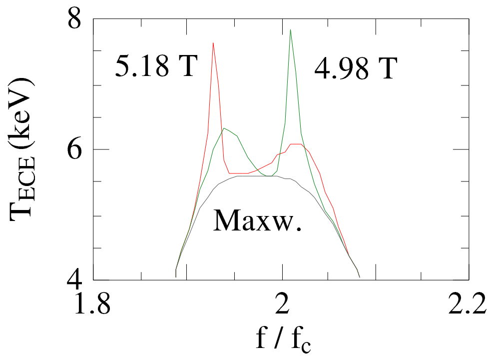

FIG. 7.

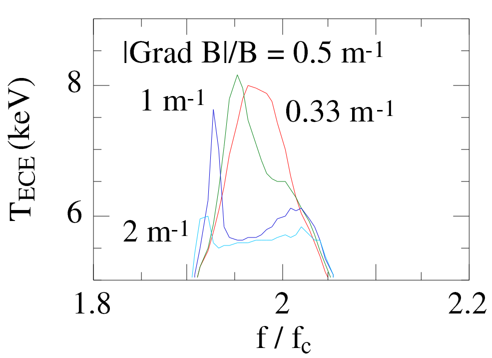

FIG. 8

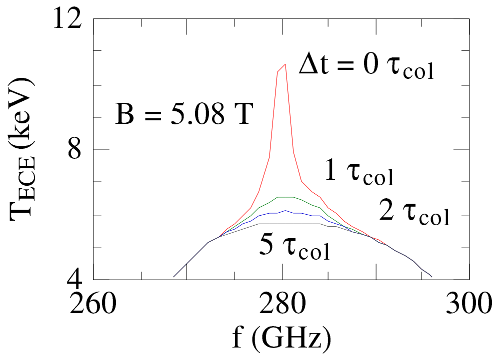

FIG. 9.

The impact of ΔB on the ECE temperature profile is studied in Fig. 8, where ∇B is varied while keeping the resonance position constant at r = 3.5 cm.

Finally, Fig. 9 shows the fast time scale associated with the relaxation of the bulk, at constant Maxwellian temperature, when the EC power is turned off (or the plasma shifts to a different position). Actual relaxation time may be larger when including the effect of the current redistribution near the resonance.[9]

Conclusions

We find that good agreement between TS and ECE temperature profiles does not imply that the electron distribution function is Maxwellian (for the case shown in Fig. 1, 25% of the energy content of the distribution function is non-Maxwellian).

Peaking of the temperature profile and large error bars in the TS profile hint that the bulk of the distribution function is non-Maxwellian. Comparison between high-resolution TS and ECE temperature measurements is needed to see this effect clearly at moderate temperatures ($T_e < 10$ keV). In hotter plasmas, the discrepancy between the two profiles is larger and directly observable.[6]

Measurement of the ECE spectra over several harmonics can identify directly the existence of this effect in high-temperature plasmas.[10,11] Preliminary comparison of simulated spectra to measured ones on FTU shows quantitative agreement (these results will be reported elsewhere).

Going back to the points listed in the Introduction, we find that:

i) Strong central temperature gradients for on-axis ECH are apparent, and caused by quasilinear flattening of the distribution function (Fig. 5).

ii) Effects on the central temperature observed in W7-AS may be due to change of ∇B in the absorption region when changing the magnetic configuration (Fig. 8). Density effects are discussed in Ref. 6. Enhancement of the collisional particle flux, induced by the non-Maxwellian bulk, may also occur. (Negligible amount of suprathermal electrons, however, is expected, contrary to the claims of Ref. 3.)

iii) Jumps of the plasma axis position, in 1% R_0 steps with period ~10 τ_{coll}, can cause filamentation of the temperature profile (Figs. 6 and 9). Temperature filamentation observed during fast time evolution of the macroscopic profiles may actually be the proof of the existence of transient non-Maxwellian states in the plasma.

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