

A KINETIC STUDY OF ECRH IN FTU

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1. Introduction

The availability of high-frequency, long-pulse, and high-power gyrotrons has spurred, in the last years, many new ECRH experiments around the world. Among them, the ECRH experiment in FTU is the one that – in terms of density range and toroidal field – is the nearest to the operational regime of a tokamak reactor, and as such has the potential for contributing to several issues that are critical to its working: the sustainment and control of the current density profile, the access to enhanced regimes of confinement, and the control of tearing-mode instabilities.

The understanding of the basic ECRH physics appears to be sound, and this makes us confident that those goals can be achieved. However, this confidence is probably based much more on the global success of past EC heating experiments, than on the detailed agreement between theoretical predictions and experimental measurements, which has never been fully tested. In fact, it is excruciatingly difficult to measure something that takes place in the very small plasma volume near the EC resonance where the RF power is absorbed. The detailed understanding of the heating process at high power-densities, however, may prove to be crucial in current drive experiments, where the interpretation of past experiments has appeared to be tricky: one basic difficulty is that – since the current generation is a relatively slow process that takes place in the tail of the electron distribution – kinetic and transport time scales stop to be clearly separated; in addition, since the current density profile in hot plasma evolves slowly, the radial diffusion of the inductive electric field has to be coupled with the kinetic equation. Another important issue is that – since most of the non inductive current is carried by nonthermal electrons – good diagnostics of the nonthermal electron distribution should be available, and some specific ones should be developed.

The consistent calculation of kinetic and transport phenomena requires one to perform all calculations at the fastest time-scale, the kinetic one: to a certain extent, this is only a problem of computational muscle, and, luckily enough, is one that today's massive parallel computers are perfectly capable of solving in a reasonable time. On the other hand, good diagnosis of the electron distribution function – or the lack of it – is an issue that, hopefully, will be recognized as such, and faced when EC current drive experiments become more widespread, and part of the mainstream, which is bound to take some time.

In this paper we present some kinetic calculations of the evolution of the electron distribution function during ECRH in FTU-like plasmas, and emphasize its impact on standard diagnostics sensitive to nonthermal electrons (EC and XR emission). We make use of a new parallel solver of the kinetic equation that reduces substantially the time required by this type of computations, which we now measure in minutes rather than in hours.

2. Parallel Solver for the Kinetic Equation

We solve the 3D kinetic equation (1D in configuration space, 2D in momentum space) with a second generation parallel code: the first generation code was based on autotasking directives and ran on Cray parallel vector computers; the present version is based on the high performance message passing library SHMEM, and runs on both Cray parallel vector, and massively parallel (RISC based) computers.

The simplest possible parallelization strategy was followed, and each configuration grid point was put on a different processor, this being the only feasible strategy on the Cray-T3E computer available at CIEMAT, which has only a modest number of processors, and also the only possible on the Cray-J90s. A substantial effort was devoted to memory bandwidth optimization on the Cray-T3E, which required a substantial rewrite of the code.

The results presented in this paper were computed on a $16 \times 190 \times 190$ 3D grid ($r \times u \times \theta$) in phase-space. On each magnetic surface, the EC quasilinear diffusion term was discretized on a 21×127 grid ($\chi \times N_{\parallel}$, with χ the poloidal angle). Typical computation time on the Cray-T3E 900 is about $1.3 \mu\text{s}$ per 3D grid point and time iteration.

2. Kinetic Results

We present a qualitative discussion of some points relevant to the ECRH experiment on FTU: quasilinear absorption, current generation, XR and EC emission are discussed for normal and oblique injection. For simplicity, concentric magnetic surfaces are assumed and Ohmic fields neglected: only the basic dependence on density, temperature, power level and injection angle is considered. The kinetic equation was solved up to the time $\tau = 50 \tau_{\text{coll}}$, with time steps in the range $\Delta\tau = 1.25 - 5 \cdot 10^{-3} \tau_{\text{coll}}$.

Figure 1 shows that in the case of perpendicular heating there is an enhancement of the plasma pressure, due to the modification of the distribution function, which varies with the density value. Inspection of the level curves of the distribution function at the point of maxi-

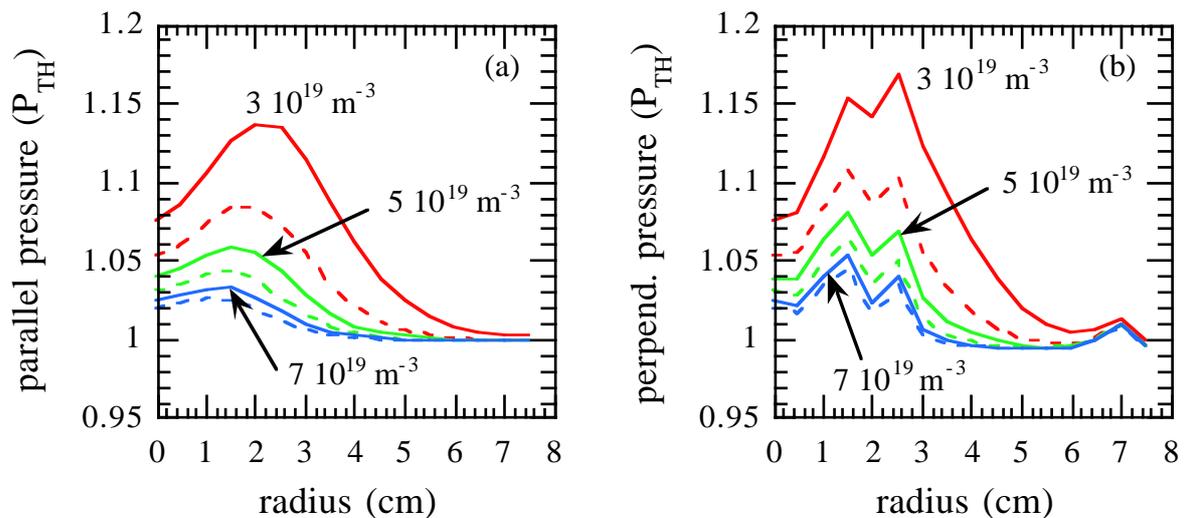


Fig. 1 The parallel (a) and perpendicular (b) pressure are computed with the Fokker-Planck distribution function, and normalized to the thermal values, for different (regularly spaced) densities. (Resonance on axis, central temperature 8 keV, wave frequency 140 GHz, 700 kW perpendicular heating in the ordinary mode.)

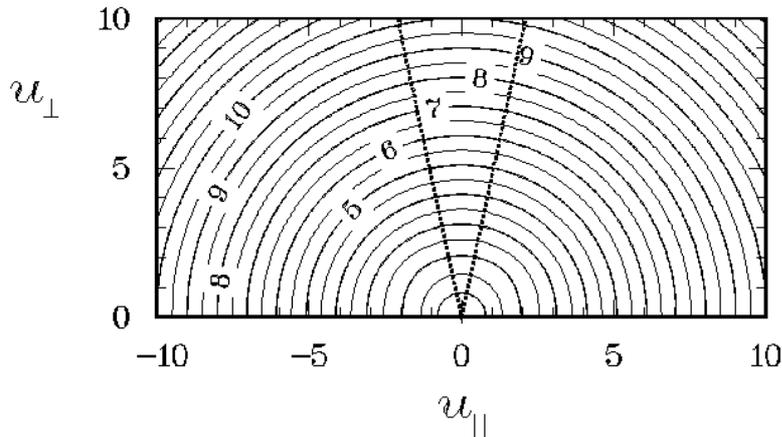


Fig. 2 Level curves of the distribution function at $r = 2$ cm, for central density $3 \cdot 10^{19} \text{ m}^{-3}$.

mum enhancement (Fig. 2) reveals only a slight modification of the distribution function in the thermal range. Figure 3 shows, however, that there is an appreciable increase of the perpendicular energy of the distribution function in the bulk (a), which is also apparent from the flattening of slope of the energy distribution (b).

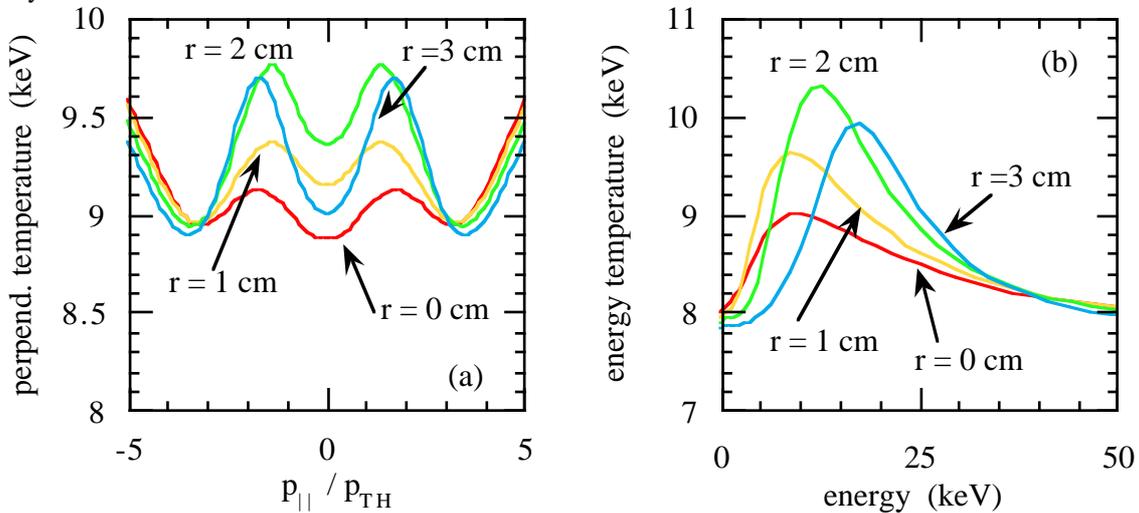


Fig. 3 Distortion of the bulk of the distribution function as shown by the perpendicular temperature (a), and the energy temperature (b) (i.e., average energy of the distribution function integrated over the perpendicular momentum, and temperature of the distribution integrated over the pitch-angle), for central density $3 \cdot 10^{19} \text{ m}^{-3}$.

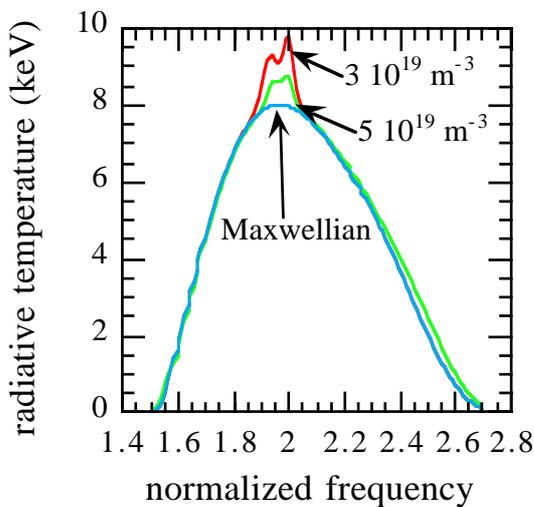


Fig. 4 Radiative temperature profile for two different densities, compared with the thermal case.

The effect of the modification of the bulk of the distribution function on standard electron temperature measurements is presented in Fig. 4: a hot spot in the temperature profile appears near the EC absorption region. It is evident that the modification of the bulk perpendicular energy causes a significant perturbation of the electron temperature measurement, and actually makes the use of the very concept of temperature inappropriate. The absence of downshifted emission in the ECE spectra, and the completely thermal X-ray emission spectra, on the other hand, show that this is

not the familiar nonthermal plasma, having a tail of energetic electrons, we are accustomed to. Instead, this is a plasma with a distorted bulk.

This distinction is stressed further on when one considers oblique heating for current drive: the X-ray spectrum is nonthermal (Fig. 5), downshifted electron emission is also present, but the bulk is not distorted, and the radiative temperature coincides with the electron temperature in the remaining part of the spectrum (Fig. 6). Noninductive current is generated by upshifted absorption of the EC waves: the current drive efficiency increases with power up to a certain threshold power-level, which depends on the parallel spectrum width (Fig. 7).

The quasilinear modification of the damping, in all the cases discussed here, is small: it is completely negligible in terms of variation of the total absorbed power, and it manifests itself only in small shifts of the power deposition profile.

4. Summary

A new parallel kinetic code, that makes it possible to compute the electron distribution function at high resolution in the phase and spectral space, is used. For FTU parameters we find that:

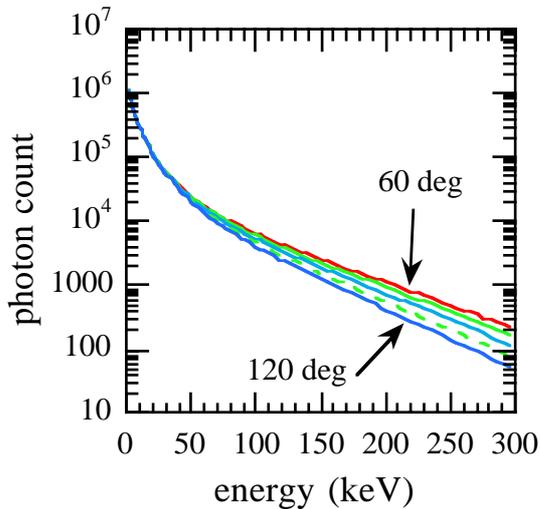


Fig. 5 XR emission spectra for oblique heating (20°) and central density $3 \cdot 10^{19} \text{ m}^{-3}$.

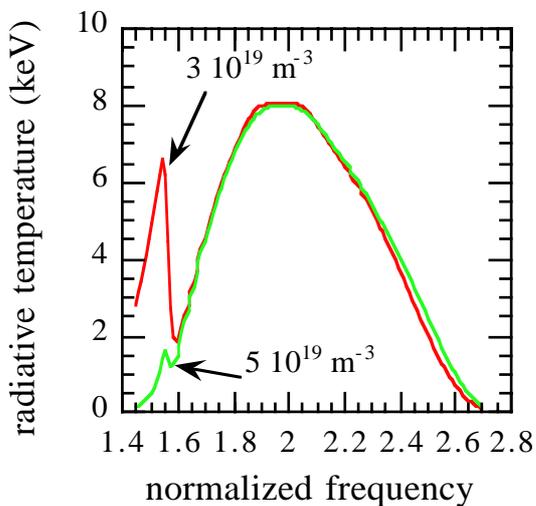


Fig. 6 Radiative temperature corresponding to Fig. 5.

i) perpendicular EC heating can cause the distortion of the bulk of the electron distribution function; this appears as a hot spot in the ECE spectra. Such a feature has been observed in many ECRH experiments, and this is the first kinetic simulation showing a similar effect.

ii) the upshifted current drive efficiency is a nonlinear function of the injected power and the parallel spectrum width.

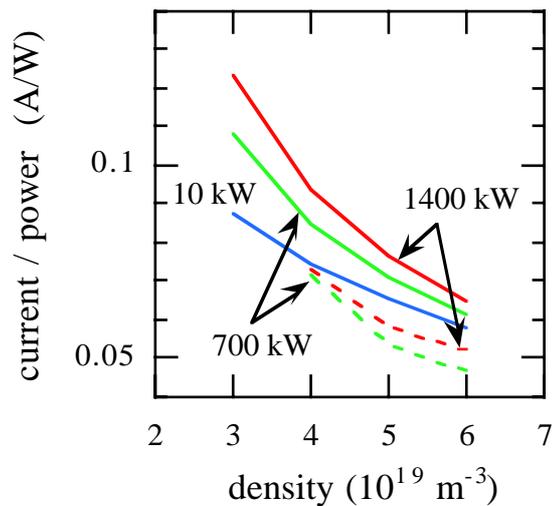


Fig. 7 Current drive efficiency for different values of the injected power, and two widths of the parallel spectrum: 5° (solid curves) and 10° (dashed curves).