FOKKER-PLANK SIMULATION OF THE ELECTRON-CYCLOTRON HEATING AND CURRENT DRIVE AND ELECTRON-CYCLOTRON/ LOWER-HYBRID SYNERGY FOR TdeV

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Electron-cyclotron (EC) heating and electron-cyclotron/lower-hybrid (LH) current drive synergy experiments are currently being done for TdeV [1], with the available 1 MW of LH power at 3.7 GHz and 0.7 MW of EC power at 110 GHz (harmonic 2 ω_{ce}). We present a study using a bounce averaged Fokker-Planck code for this problem. The code makes use of an accurate relativistic collision operator presented and discussed in Refs. [2, 3]. The Fokker-Planck equation is discretized in momentum space using a nine-point scheme, and solved using an efficient nine-point algorithm solver [4]. Details of the code and the pertinent equations have been presented in Ref. [5]. For the case of a synergy between the EC wave and the LH wave, we consider the practical case where the LH deposition profile is peaking off-axis, and hence the interaction between the LH and EC waves has to take place off-axis. We assume that this interaction is taking place on a flux surface of radius R_{min} = 5 cm. We present in Fig. 1 the results obtained when the interaction takes place at poloidal angle θ = 45º. With $\in = R_{min} /R_{maj}$ (for TdeV the major axis R_{maj} = 83 cm) we get $2\omega_{ce}/\omega = 1/(1+\in \cos\theta)$ = 0.96. The quasilinear diffusion operator for the EC wave was written in Ref. [5] for the harmonic 2 ω_{ce} as

$$D = D_{cy} \frac{\gamma}{|p_\parallel|} p_\perp^2 \exp\left(-\left(\left(\gamma - \frac{2\omega_{ce}}{\omega} \right) \middle/ (p_\parallel \beta_{th}) - N_\parallel \right)^2 \middle/ \Delta N_\parallel^2 \right) \tag{1}$$

where $p_\parallel$ and $p_\perp$ are the parallel and perpendicular components of the momentum, $\gamma = \left(1 + p^2\beta_{th}^2\right)^{1/2}$. The following parameters pertinent to TdeV were chosen: T_e = 2 keV, β_{th} = 0.0442 $\sqrt{T_e}$, $N_\parallel$ =0.4, $\Delta N_\parallel$ =0.005 and D_{cy} = 0.01. Away from the resonance (2 ω_{ce}/ω = 0.96) and at $N_\parallel$ = 0.4 (corresponding to an oblique toroidal angle of injection of about 20º), the EC wave alone generates little current (j = 2.59 × 10⁻³, P_{abs} = 5.2 × 10⁻⁵, j/P_{abs} = 50.). These results are presented in the top row of Fig. 1, which shows that the EC wave has little effect on heating the bulk, but generates a small hot population in the tail

which provides the moderate current we get. The last figure in the row plots the parallel distribution as function of energy. The LH results (calculated with a quasilinear diffusion operator with $D_{LH} = 0.5$ acting over a parallel velocity range $3 < p_{||}/\gamma < 6$) are presented in the middle row and provide a current of $j = 9.24 \times 10^{-2}$, $P_{abs} = 5.0 \times 10^{-3}$, $j/P_{abs} = 18.2$. The synergy between the LH wave and the EC wave is presented in the bottom row of Fig. 1. The EC wave is interacting with the plateau of the LH wave to provide an efficient synergy in the value of the current. In this case $j = 0.123$, substantially higher than the sum of the individual LH and EC currents. With $P_{abs} = 5.74 \times 10^{-3}$, this results in a ratio $j/P_{abs} = 21.4$. These results are consistent with what have been recently reported in Ref. [6] of a strong synergy between the LH and EC in the case of oblique toroidal injection of the EC wave. One might expect that a stronger synergy would exist if $2\,\omega_{ce}/\omega$ was closer to 1 but this is not so. Figure 2 presents the result obtained when θ is fixed such that $2\,\omega_{ce}/\omega = 0.988$, on the same flux surface $R_{min} = 5$ cm. We are indeed closer to the vertical axis where the second harmonic resonance occurs, and the resulting EC current is stronger ($j = 4.6 \times 10^{-2}$, $P_{abs} = 5.4 \times 10^{-4}$, $j/P_{abs} = 85$, top row in Fig. 2). The LH result in the middle row of Fig. 2 is close to what is presented in the corresponding row in Fig. 1 ($j = 9.05 \times 10^{-2}$, $P_{abs} = 5.0 \times 10^{-3}$, $j/P_{abs} = 18.1$). Trapping is much more important in this case and there is no synergy between the LH and EC wave with $N_{||} = 0.4$ ($j = 8.15 \times 10^{-2}$, $P_{abs} = 4.97 \times 10^{-3}$, $j/P_{abs} = 16.4$). Note how the distribution function is contracting with respect to the bottom row in Fig. 1. These results appear to be in good qualitative agreement with experimental results from TdeV [7].

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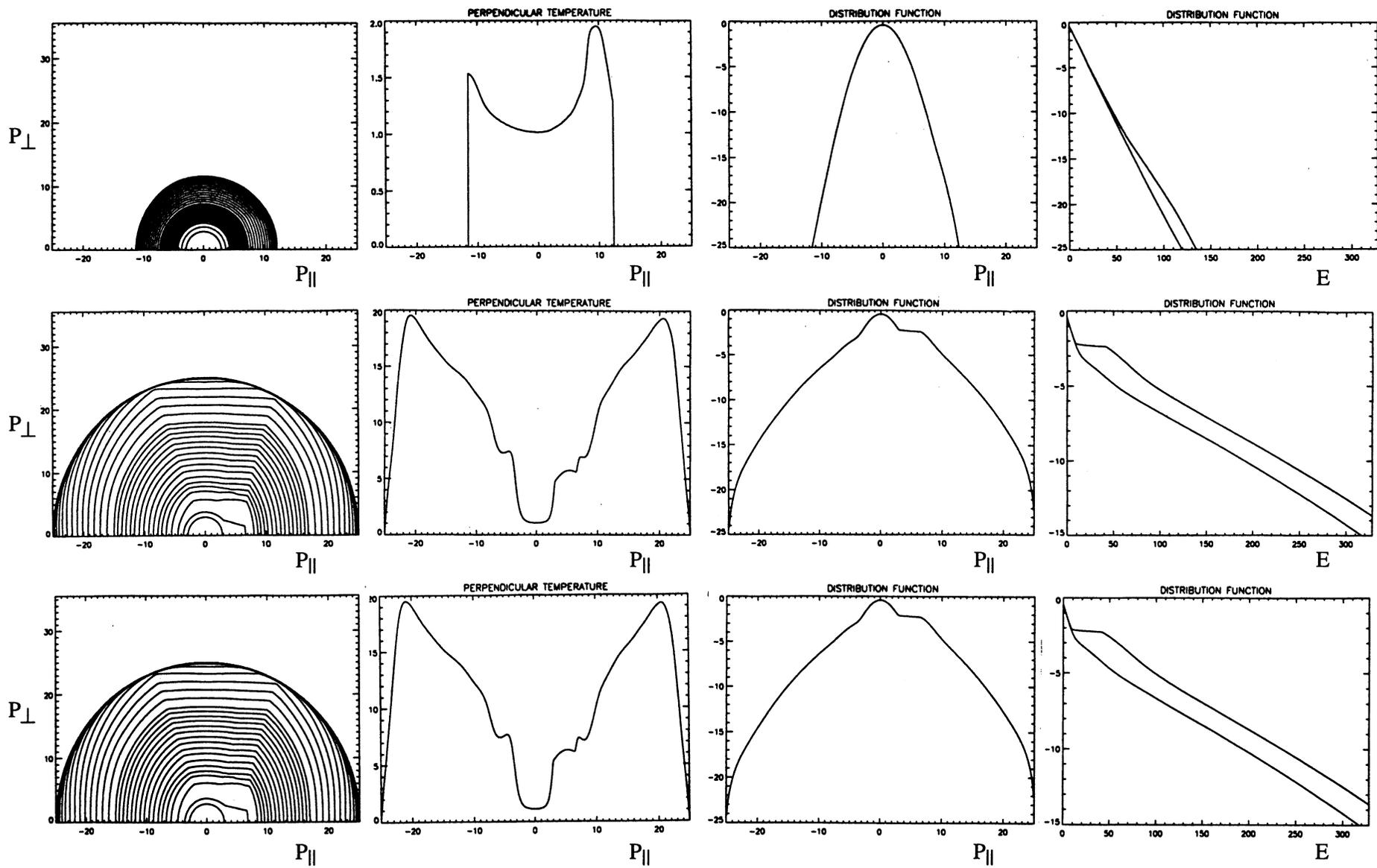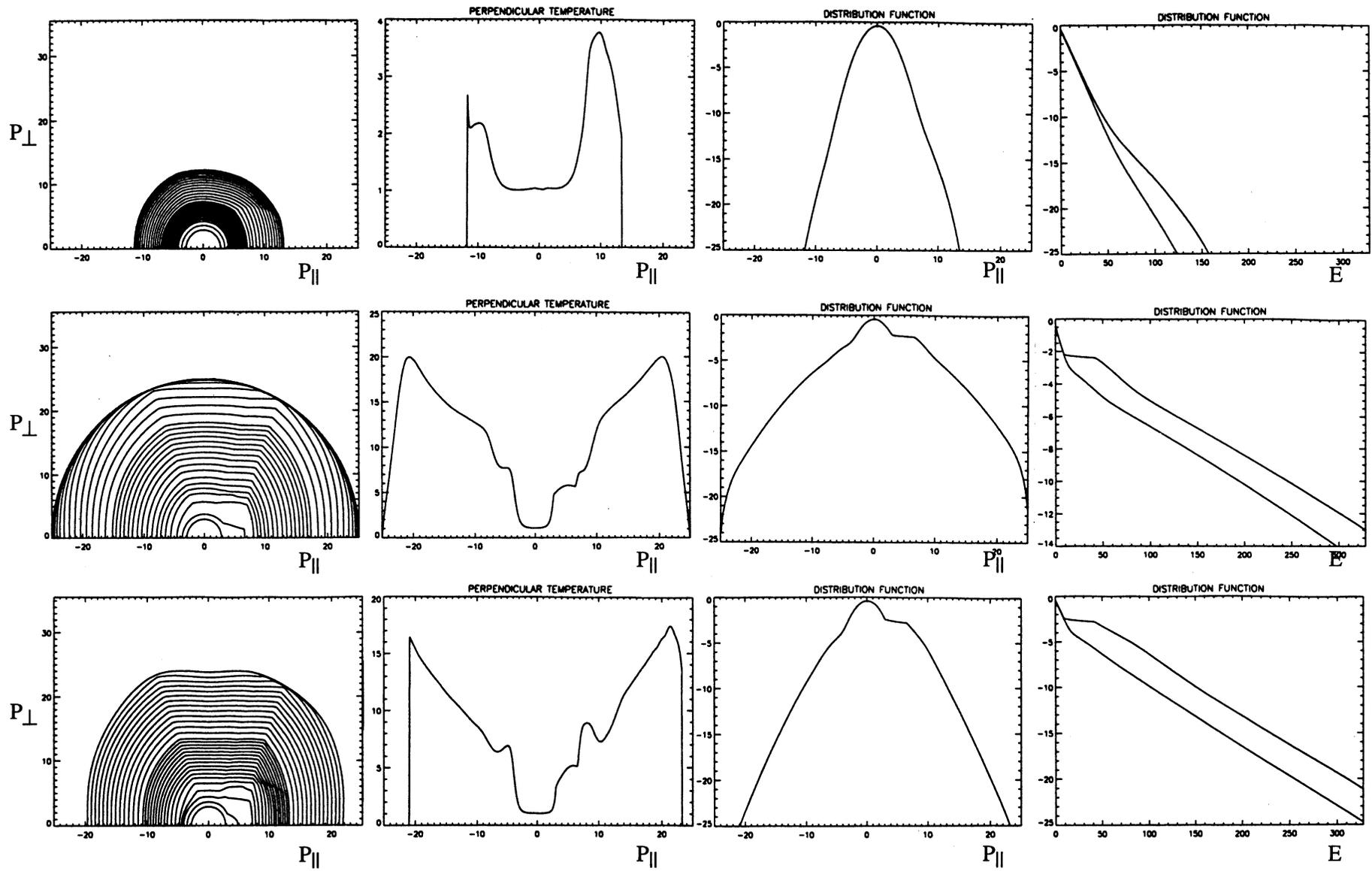
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Figure 1

Figure 2