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ABSTRACT

The CQL3D Fokker-Planck code is used to investigate effects of quasilinear distortion of the electron tail in the T–10 second harmonic electron cyclotron current (ECCD) drive experiment. The experiment operates in a regime of substantial tail formation. Current drive efficiency may be doubled relative to low power cases. That portion of electric field-driven current which is synergetic with the rf-induced nonthermal tail may tend to cancel the ECCD current in relevant cases.

The T–10 second harmonic electron cyclotron current drive (ECCD) experiment[1] consists of injection of $\sim$ 1 MW of power from the outside equatorial plane of the tokamak. Due to the small beam divergence, 3 degrees FWHM, of the injected power, very high absorbed power densities are obtained for current drive near the magnetic axis. These power densities $p_{EC} \sim 10$ W/cm^3 strongly exceed the criterion for quasilinear electron tail formation by ECH,[2] $p_{EC} > 0.5\, n_{13}^2$ W/cm^3 where n_{13} is the density in units of 10^{13} cm^{-3}. Consequently, substantial nonthermal electron tails have been anticipated, and observed, in the experiment.

The experiment is operated in a regime where the ECCD provides less than the total plasma current and thus a toroidal voltage continues to exist in the steady state plasma, Ohmically driving the remainder of the total plasma current. Typical total plasma current in the experiment is 80 to 140 kA. The nonthermal tails produced by the ECH can carry energy comparable to the bulk plasma, and thus it is also expected that there will be substantial additional current beyond what is calculated with with Spitzer conductivity due to the action of the toroidal electric field acting on the nonthermal tail. This additional current, beyond the simple Ohmic and ECCD currents, is referred to as "synergy current." As will be seen below for the T–10 cases, this synergy current can be as large as the ECCD current.

A further aspect of the experiment which must be considered is that the resistive time of the plasma may be longer than the EC pulse length. Consequently, the internal loop-voltages may differ significantly from the values observed at the plasma periphery. Thus, the resistive time can be estimated from

$$\tau_{\text{resistive}} = \frac{4\,\pi r^2}{\eta_{\parallel} c^2} = 1.0 \text{ sec} \quad ,$$

assuming $r = 0.2\,a$, $T_e = 5$ keV, $Z_{\text{eff}} = 2$, whereas the EC pulse length is typically $\sim$ 0.4 sec. In a consistent manner, ONETWO[3] transport code simulations of a typical discharge, using a simple model for sawtoothing instability which spreads the EC current drive so that the safety factor on axis, q_0, remains greater than 1.0, shows that the internal inductive effects remain for up to about 1.0 sec; that is, this period is the persistence time for the Lenz's law type shielding of the the applied rf current

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by induced toroidal electric field and Ohmic current. (A more elaborate modeling of sawtoothing T–10 discharges by Forest *et al.*,[4] accounting for Kadomtsev's conservation of helical flux[5] during the sawtooth crash, reveals a very interesting electric generator effect when the central rf driven current exceeds the the pre-rf Ohmic current. Quasi-steady negative voltages to ~ -0.5 V appear near the magnetic axis, for a co-current simulation.)

The CQL3D FP code[6] is well suited to exploring the effects of the interaction of rf and toroidal electric fields. The steady state of the electron distribution function f_e and the radial rf absorption profile are obtained by iteration between (1) the Guassian elimination solution of the Fokker-Planck equation for the steady state f_e at each flux surface

$$\frac{\partial f_e}{\partial t}\left(u_{\parallel 0}, u_{\perp 0}, \rho, t\right) = \left\langle \frac{eE_{\rm DC}}{m} \cdot \frac{\partial f}{\partial \underline{u}} \right\rangle + \langle \mathcal{C}(f) \rangle + \langle \mathcal{Q}(f) \rangle = 0 \quad , \tag{1}$$

where $u_{\parallel 0}$, $u_{\perp 0}$ are momentum-per-mass of electrons at the outer equatorial plane of each flux surface, $\langle\ \rangle$ indicates a bounce-average; and (2) the rf energy transport equation integrated along a ray

$$\nabla \cdot v_g \mathcal{E} = - \int du\,(\gamma - 1)\, mc^2\, \mathcal{Q}(f) \quad , \tag{2}$$

where v_g is the ray group velocity, $\mathcal{E}$ is the energy density. In Eq. (1), $\mathcal{C}$ is the full collision operator linearized about a Maxwellian distribution shifted in the $u_\parallel$-direction to conserve momentum in the electron-electron collision process. The quasilinear operator $\mathcal{Q}$ is the full operator for the finite gyroradius cyclotron interaction generalized to include the effects of relativity. The launched spectrum of rf energy is discretized into a set of rays which are injected from the plasma periphery. The rays are further discretized into short length elements, each of which contributes to the operator $\mathcal{Q}$, and the damping of the ray element is self-consistently obtained using Eq. (2). The damping rate agrees well with standard expressions.

Using the T–10 EC injection geometry — *viz.*, injection from the outside equatorial plane at 21 deg from perpendicular at the plasma edge, 140 GHz, X–mode — a series of runs were made varying the plasma density, EC power, and loop voltage. The on-axis toroidal magnetic field was chosen to be 2.45 T so that the power deposition and current drive were strongly localized near the magnetic axis, and central temperature is 4 keV. The results from these runs are given in Figs. 1 and 2.

The current $I^*_{\rm rf}$ is the total plasma current driven by the combination of EC power and applied toroidal loop voltage ($I_{\rm total}$) minus the Ohmic current ($I_{\rm ohmic}$) obtained from the code with only the loop voltage turned on: $I^*_{\rm rf} = I_{\rm total} - I_{\rm ohmic}$. Thus the current $I^*_{\rm rf}$ is the sum of the ECCD current and the toroidal electric field synergy current.

Figure 1 shows $I^*_{\rm rf}$ versus EC power, for several values of loop voltage $V_{\rm L}$ and for co- and counter-rf injection. Fig. 1(a) is for central density $n_{e0} = 1.05 \cdot 10^{13}\,{\rm cm}^{-3}$ and loop voltages 0.0 and 0.4 V. Fig. 1(b) is for a less extreme case of density $n_{e0} = 1.3 \cdot 10^{13}\,{\rm cm}^{-3}$ and loop voltage to 0.25 V. The dashed lines in Fig. 1 are linear extrapolations of the low power results given in the diagrams. Thus in Fig. 1(a) for the loop voltage $V_{\rm L} = 0.0$ V-case, the driven current more than doubles at the highest powers over the linear results. This increase in current drive efficiency is due to formation of a nonthermal tail[2] within the central 15% of the minor radius. For

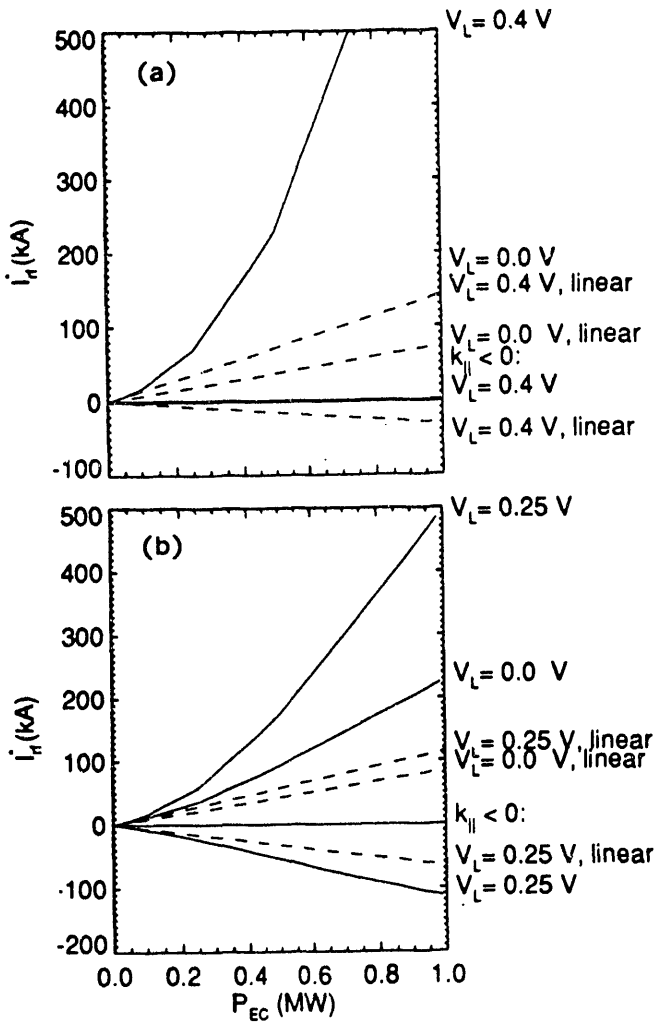

FIG. 1. The driven current I_{rf}^*, equal to the sum of the ECCD current and the toroidal electric field synergy current, versus EC power. The solid curves give code results and the dashed lines are extrapolation of the low power results for (a) central density $n_{e0} = 1.05 \times 10^{13}\,\mathrm{cm}^{-3}$, and (b) $n_{e0} = 1.3 \times 10^{13}\,\mathrm{cm}^{-3}$.

the co-current ECCD-case combined with $V_L = 0.4$, the tail electrons essentially run away at the high power and the resulting current depends on the maximum energy on the computational grid (250 keV in these cases). The linear extrapolation (dashed line) for this case underestimates the calculated current even at quite low power, and thus linear calculations of this "hot conductivity" effect will not be sufficient. For the counter-current drive case ($k_{\parallel} < 0$ and $V_L = 0.4$), the net current I_{rf}^* even changes sign above an rf power of 750 kW. This corresponds to the synergy current exceeding the ECCD in magnitude.

Figure 1(b) for the less extreme case $n_{e0} = 1.3 \cdot 10^{13}\,\mathrm{cm}^{-3}$, $V_L = 0.0$, 0.25 V still exhibits the doubling of the current drive efficiency beyond linear estimates, and the large synergy current as in the co-current case of Fig. 1(a). However, for the counter-current case, the synergy current does not lead to a reversal of the net driven current I_{rf}^*.

Figure 2 gives I_{rf}^*, the ECCD + synergy current, versus loop voltage. Thus, the extent to which I_{rf}^* is not equal to its value at $V_L = 0.0$ V gives the synergy current. In Fig. 2(a), the EC power P_{EC} is a parameter and density is $n_{e0} = 1.3 \cdot 10^{13}\,\mathrm{cm}^{-3}$. Negative loop voltage V_L corresponds to counter-current drive. We note that for $V_L \sim -0.4$ V the synergy and ECCD currents cancel quite independent of power from 200 to 800 kW.

In Fig. 2(b), density is the parameter with rf power held fixed at $P_{EC} = 400$ kW. The voltage for cancelling of the ECCD and synergy current, *viz.*, the voltage at which $I_{rf}^* = 0.0$, is seen to be a quite strong function of density. Synergy current will be an important component in the present experiments.

It can be surmised from the results in Fig. 2 that the MHD-generated negative voltage ~ -0.5 V occurring in the simulation of T-10 reported by Forest *et al.*[3] will

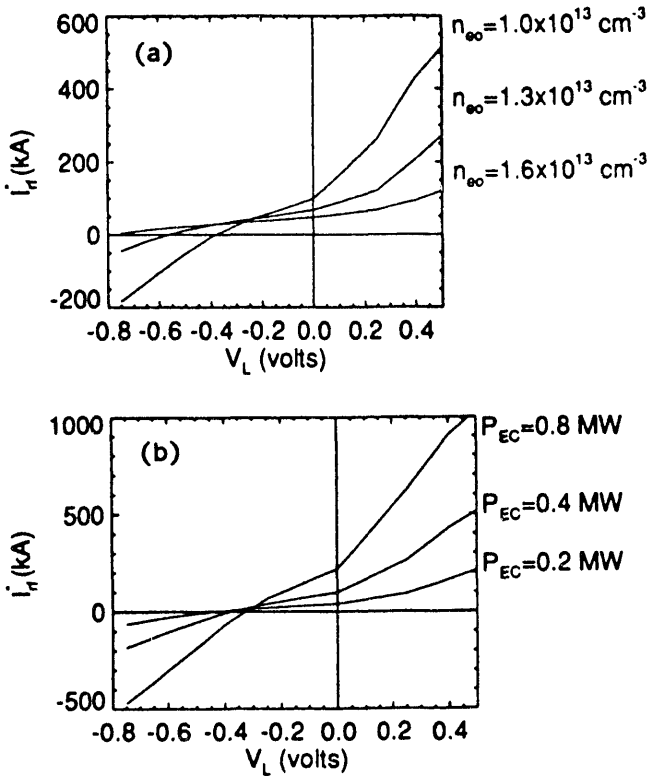

FIG. 2. I_{rf}^* versus toroidal loop voltage with (a) EC power as parameter, and (b) central density as parameter. The temperature is 4 keV.

be closer to an intermediate value ~ 0.25 V if the results presented here are accounted for.

In summary, an accurate interpretation of T–10 experimental voltage traces must take into account the inductive effect and the interaction of the toroidal electric field with the quasilinear distortion of the electron tail.

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