Current drive by electron-cyclotron and lower hybrid waves in the T-7 tokamak

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A current-drive method based on microwaves in the region of the electron cyclotron resonance in tokamaks has been studied. The initial plasma has an asymmetric plateau on its electron velocity distribution.

The use of microwaves in the region of the electron cyclotron resonance (ECR) for current drive in tokamaks is attractive for several reasons: The localization of the power deposited in the plasma is determined by the strength of the toroidal magnetic field; there is the hope that a selected current profile can be formed and sustained in the plasma; sawtooth oscillations are stabilized; etc. Theoretical work predicts a relatively high efficiency for electron-cyclotron current drive in a Maxwellian plasma with an electron temperature $T_e \geqslant 10$ keV (Ref. 1). At electron temperatures $T_e \cong 1$–5 keV, it is apparently possible to detect a significant ECR current in a non-Maxwellian plasma. Accordingly, in the experiments which we are reporting here we started with a plasma in which a plateau was formed up to an energy ~ 60 keV on the longitudinal-velocity distribution of the electrons ("longitudinal" here means with respect to the magnetic field). The plateau was formed with the help of lower hybrid (LH) waves.

Experimental procedure. The experiments were carried out in the T-7 tokamak ($R = 122$ cm, $a = 35$ cm).[2] Lower hybrid waves were excited in the plasma by a phased three-waveguide source.[3] The power of the LH waves deposited in the plasma,

P_{rf}, was 110 kW. The spectral density of the power had a maximum at a longitudinal slowing $N_z = 3$ (z is the direction of the toroidal magnetic field) in the direction of the electron current. The source of the ECR power was a gyrotron ($P_{mw} \leqslant 400$ kW, $f_g = 80$ GHz). Microwave energy in the form of ordinary waves was transported to the tokamak chamber through an oversized waveguide (80 mm in diameter) from the side of the weak magnetic field. After passing through the plasma column essentially unabsorbed, the radiation struck a corner reflector on the rear wall of the vacuum chamber. The reflected power, with a polarization corresponding to an extraordinary wave, propagated at an angle $\alpha \approx 80°$ with respect the toroidal magnetic field in the

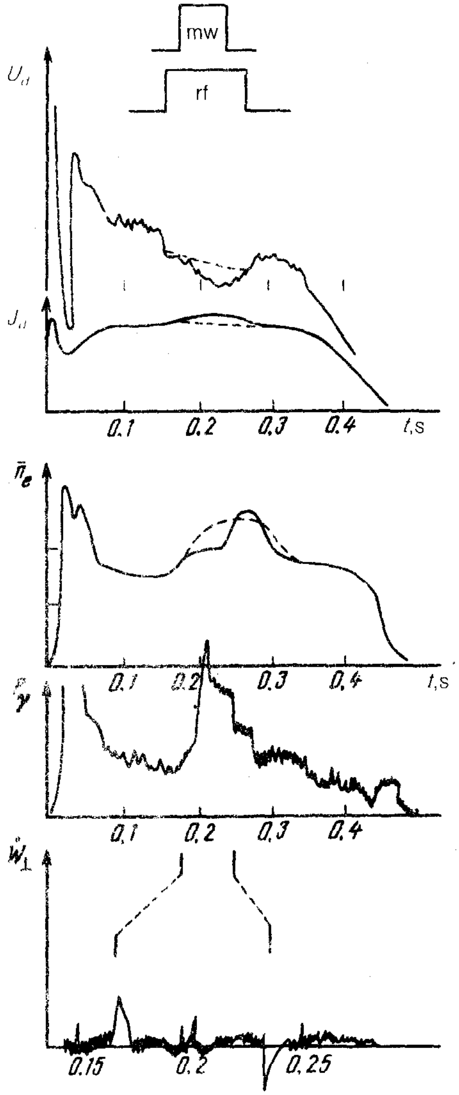

FIG. 1. Oscilloscope traces: the discharge voltage U_d; the plasma density averaged along a central chord, $\bar{n}_e$; the radiative loss from the plasma, P_r; the derivative of the diamagnetic signal $\dot{W}$ ($P_{rf} = 110$ kW, $P_{mw} = 360$ kW, $\gamma = 1.112$).

direction opposite the electron current velocity. Experiments were carried out at toroidal fields $H_T = 1.4–1.8$ T (near the second ECR harmonic).

Experimental results. Figure 1 shows oscilloscope traces of the basic discharge parameters during operation of the LH system and during joint operation of the LH and ECR systems. The LH source operated for 120 ms in this series of experiments. The gyrotron was turned on 20 ms after the beginning of the operation of the LH system; the length of the microwave pulse from the gyrotron was 60 ms. The traces shown here refer to working conditions such that the zone of the second ECR harmonic was displaced $r = 14$ cm outward from the center of the chamber ($\gamma = 2\omega_{ce}/\omega_g = 1.112$, where $\omega_g = 2\pi f_g$ is the gyrotron frequency, and ω_{ce} is the electron-cyclotron frequency at the center of the chamber). We see that the introduction of ECR power lowers the discharge voltage U_d, causes an insignificant decrease in the plasma density $\bar{n}_e$, and causes an increase in the radiative loss P_γ. The absorbed power was found from the signal representing the derivative of the plasma diamagnetic signal (Fig. 1). Figure 2 shows the behavior of the voltage across the discharge and that of the derivative of the plasma diamagnetic signal, $\dot{W}_\perp$, versus the localization of the zone of the second ECR harmonic or the value of γ. For the case $\gamma = 1.046$ (the ECR zone is localized at $r = 6$ cm from the center of the torus; r is the displacement along the minor radius), two values of $\dot{W}_\perp$ are shown. The larger value of $\dot{W}_\perp$ was found during operation of the LH system and corresponds to the ECR power which is absorbed by both thermal electrons and electrons on the LH plateau. The lower value was found by subtracting from the former the rf power absorbed in an ohmic plasma with very nearly the same parameter values, it corresponds to the power absorbed by the plateau electrons. Note that at $\gamma = 1.1$ the microwave power is absorbed in the plasma only when the LH system is operating. It is apparently related to an interaction of the ECR

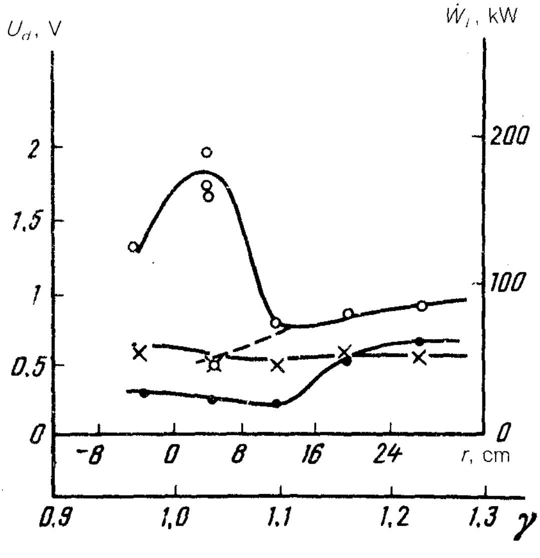

FIG. 2. Derivative of the plasma diamagnetic signal ($\dot{W}$) and the discharge voltage U_d versus the value of γ or the position of the second ECR harmonic along the minor radius of the torus (r). ○—$\dot{W}$ during operation of the LH and ECR systems; ●$\dot{W}$ during absorption of the ECR power by the electrons of the LH plateau; ×—U_d during operation of the LH system; ●—U_d during operation of the LH and ECR systems.

waves exclusively with plateau electrons. At the value $\gamma = 1.177$, i.e., in the case in which the ECR zone was localized in the immediate vicinity of the limiter ($r \approx 21$ cm), the microwave power injected into the system caused marked changes in the discharge parameters: Significant increases, by factors of 2–2.5, were observed in $\bar{n}_e$ and P_γ.

The electron temperature T_e and its distribution along the minor radius of the plasma were found from measurements of the x-ray emission spectra in the energy range from 2 to 10 keV. These measurements showed that the temperature at the center of the plasma, $T_e(0)$, depended strongly on γ at fixed value of the power injected into the chamber, P_{mw}. The largest value of $T_e(0)$ was observed at $\gamma = 1.046$; this figure corresponds to the case in which the zone at the second ECR harmonic is near the center of the plasma column. At this value, the absorbed power P_{abs} is at a maximum, and most of it is absorbed by thermal electrons (Fig. 2). At larger values of γ, at which the absorption results from the interaction of the ECR waves with the electrons of the LF beam, there was no change in $T_e(r)$, within the measurement error.

In the experiments we carried out chord measurements of the x-ray emission spectrum in the energy range $E_\gamma = 20$–100 keV during joint operation of the LH and ECR systems and also during operation of the LH system alone. From these measurements we determined the radial profiles of the x-ray emission intensity, $J(r)$, at various energies E_γ. When the LH system was operated alone, the $J(r)$ distributions for various energies E_γ were similar. As a qualitative characteristic of the localization of the LH beam in the plasma, we show the distribution $J(r)$ at $E_\gamma = 30$ keV in Fig. 3.

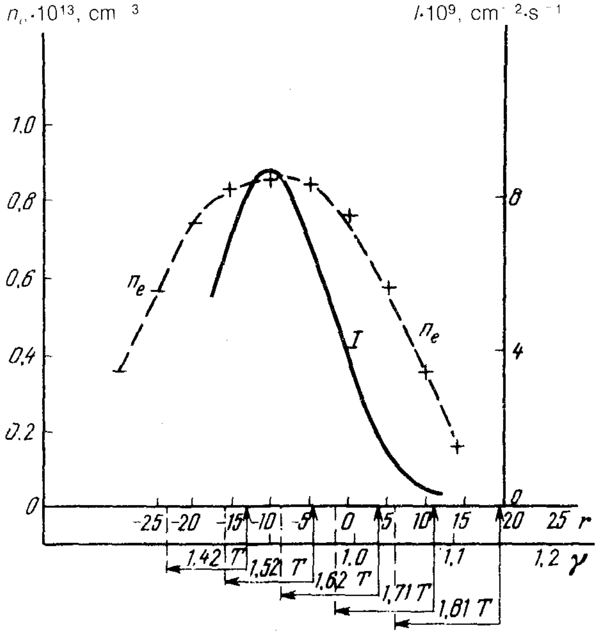

FIG. 3. Radial profile of the x-ray emission intensity, $J_\gamma(r)$, for x radiation with an energy $E_\gamma = 30$ keV during operation of the LH system, and radial profile of the density, $n_e(r)$. ↑—Zone of second ECR harmonic at $T_e = 0$; ←—region in which the absorption of ECR waves is localized along the minor radius of the torus (r) in the equatorial plane for an electron energy $E_e \approx 25$ keV (the transverse energy is $E_{e\perp} = 5$ keV), for various values of γ.

Discussion of results. The mechanism for current drive in a plasma by means of ECR waves involves a disruption of the symmetry of the longitudinal-velocity distribution of the electrons which occurs during a transverse heating of a group of resonant electrons and their accumulation in the plasma. This disruption of the symmetry becomes noticeable only if the confinement time of the deposited energy is longer than the time scale of the Coulomb collisions for the electrons which absorbed the ECR power. In the opposite case, the heated electrons rapidly lose their energy, they do not accumulate in the plasma, and the corresponding ECR current decreases. Let us discuss the results from this standpoint. We will be discussing only those electrons which have a longitudinal-velocity component in the direction opposite the ECR wave, since the resonant energy for the electrons moving in the opposite direction is high, reaching $\sim$80–100 keV, even at $\gamma \approx 1$.

It follows from the oscilloscope traces of the plasma diamagnetic signal, $\dot{W}_\perp$, that the confinement time of the transverse energy acquired by the electrons in the interaction with the ECR waves is ≈ 6 ms and does not depend on the frequency difference γ, at the values of the latter used in the experiments. In other words, it does not depend on the energy of the resonant electrons. Under the assumption that, for the most part, only those electrons for which the Coulomb collision time is shorter than 6 ms participate in the ECR current drive, we can estimate the limiting energy E^* of these electrons. Under our conditions, with $n_e = 7\times 10^{12}$ cm^{-3} (Fig. 3) and with the effective charge $Z_{\rm eff} = 2$ found from the x-ray measurements, we find $E^* = 25$ keV. From the resonance condition

$$\omega - k_\| v_\| - 2\omega_{ce}\left(1 - \frac{v^2}{2c^2}\right) = 0$$

it follows that at a given γ the electrons of the LH plateau which are participating in the current drive acquire an energy $E_e \leqslant E^*$ as they interact with the ECR wave packet only in certain regions in the plasma column. Figure 3 shows the boundaries of these regions for various values of γ. The transverse energy of the electrons for the upper boundary is $E_\perp = 5$ keV. The lower boundary of the interaction region, shown in Fig. 3, corresponds to the zone of the second ECR harmonic for the cold plasma. It can be seen from Fig. 3 that at large values of the frequency difference, $\gamma > 1.112$, it is predominantly electrons with energies $E_e > E^*$ which interact with the ECR waves. In this case, despite the absorption of ECR power by the beam electrons, we do not observe an ECR current drive; i.e., there is no change in the discharge voltage U_d (Fig. 1). At $\gamma = 1.046$, the ECR waves interact with not only the electrons of the LH beam but also thermal electrons. The interaction with thermal electrons leads to a significant increase in the electron temperature $T_e(0)$, to 3–4 keV, and thus to a significant decrease in U_d. Under these conditions it is rather difficult to determine the magnitude of the ECR current drive from the change in U_d. The best value of the frequency difference γ for observing the ECR current drive is $\gamma = 1.112$. In this case the zone of the ECR heating of the electrons of the LH plateau with $E_e \leqslant E^*$ is localized in the center of the plasma, and the region occupied by heated particles with $E_e \leqslant E^*$ is at a maximum (the rotational transform has been taken into account here; Fig. 3).

It can be seen from Fig. 2 that it is at this value that we see the maximum decrease in U_d. The additional ECR current, defined as $I_{\rm ecr} = (\Delta U_d / U_d) I_d$, where ΔU_d is the change in the discharge voltage, was 50 kA at this value of γ. The change in the discharge voltage at $\gamma = 1.112$ may also be determined by the ECR heating of electrons near the lower boundary of the LH plateau on the distribution function, where $v_\parallel = (2.2\text{–}2.5) v_{T_e}$. The decrease in the collisional diffusion coefficient should reduce the resistance for quasilinear diffusion in this region, and it may lead to an increase in the number of particles over the entire LH plateau, i.e., to an increase in the LH current.[3]

[1] Nucl. Fusion **27**, 579 (1987).

[2] V. F. Denisov, D. P. Ivanov *et al.*, VANT, No. 1 (.7) (1981).

[3] Plasma Physics and Controlled Nuclear Fusion Research; Proc. IX Conference (Baltimore, 1–8 Sept. 1982), Vol. II, 1982, pp. 153–161.

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