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Experimental Observation of the rf-Driven Current by the Lower-Hybrid Wave in a Tokamak

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(Received 4 February 1980)

It is observed that the waves launched from a phased array antenna of four waveguides couple effectively with electrons under the condition of $\omega_0/\omega_{lh}(0) \gtrsim 2.0$. This coupling generates a rf-driven current, rather than heating of the bulk electrons, and the current/rf-power ratio of 110 A/kW was obtained with a rf power of 125 kW radiated into a plasma which included appreciable suprathermal electrons.

PACS numbers: 52.35.Fp, 52.35.Mw, 52.40.Fd, 52.50.Gj

A tokamak, which is the most successful device now on the road to controlled fusion, has the major disadvantage of pulsed operation because of a need to induce a toroidal current in the plasma. The application of rf to drive the current in steady-state tokamak reactors has been considered by a number of authors.[1-5] A method of producing continuous current carried by electrons in the tail of distribution function via quasilinear Landau damping of high-phase-velocity rf waves near the lower hybrid (LH) frequency has been proposed.[4,5] The linear and quasilinear Landau damping of slow electrostatic waves near LH frequency has been confirmed in a linear test device[6] and in the LH electron heating experiment on the tokamak (Doublet IIA).[7] These experiments provide a physical base for understanding the quasilinear Landau damping in the toroidal plasma with a relatively high electron temperature. Recently, the current generated by the unidirectional electron plasma waves has been observed in linear devices[8,9] and a toroidal device.[10] These experiments have been carried out in a plasma with a lower electron temperature, in which a transfer of momentum from LH waves to electrons via collisional absorption is significant.

In order to make effective coupling between the LH waves and electrons, it is necessary to avoid the deposition of the rf energy into ions resulting from the linear mode conversion and the excitation of parametric instabilities. The previous experiments on the rf ion heating indicated that for $\omega_0/\omega_{lh}(0) \gtrsim 1.6$ the ions did not interact with the rf waves and the parametric decay instabilities almost disappeared,[11,12] where ω_0 is the frequency of the applied rf field and $\omega_{lh}(0)$ is the LH frequency at the center of the plasma column. In this Letter, we report the experimental study on the coupling between the rf waves and electrons under the conditions of $\omega_0/\omega_{lh}(0) \gtrsim 2$ and the relatively high electron temperature in a tokamak.

The experiment, with a 750-MHz rf source, was performed in the JFT-2 (JAERI Fusion Torus) tokamak, which was a conventional tokamak with a major radius of $R_0 = 90$ cm and a minor radius of $a = 25$ cm. The experimental setup and the discharges were reported in detail,[13] and hence will be described only briefly here. In the present experiment, the following discharge was used as a magnetohydrodynamically stable operation; toroidal magnetic field $B_t = 14$ kG, plasma current $I_p = 30$ kA, mean line-of-sight electron density $\bar{n} \simeq 3\times10^{12}$ cm^{-3}, central electron temperature $T_{e0} \simeq (250\text{ eV})/k$ and effective ionic charge Z_{eff} of 2–5. The working gas was deuterium. The waveguide array employed here consists of four independently driven waveguides mounted 1.5 cm away from the plasma edge, which is defined by

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a limiter; each waveguide has inner dimension of 1.4 cm by 29.0 cm. Toroidally, the array antenna is located 90° away from the limiter. By selecting the relative phases among the waveguides, peak values of parallel refractive index n_z of the vacuum electric field can vary between 0 and 12. The energy of launched waves is expected to be directed upstream or downstream of electrons by the appropriate phase difference between adjacent waveguides $\Delta\varphi$.

Data from a typical plasma experiment for applied rf power of $P_{\rm rf} = 100$ kW and $\Delta\varphi = 90°$ are shown in Fig. 1. The dotted curves of Fig. 1 correspond to no rf conditions. The rf pulse is found to produce marked decreases in the loop voltage V_1 and the hard-x-ray emission H_x, a dramatic enhancement of the electron cyclotron emission I_c, and no effect on the electron density and the plasma current. The cyclotron emission was detected by a heterodyne radiometer having the local oscillator with frequency corresponding to the second-harmonic cyclotron frequency at the major radius of $R \simeq 101$ cm. The hard-x-ray emission, which radiates from the limiter bombarded by accelerated electrons, was measured by a NaI scintillator. The detectable energy range was 10–100 keV. The loop voltage falls to nearly its time-asymptotic level in about 0.6 msec after the rf pulse is turned on. The cyclotron radiation increases linearly in time until a sudden increase is seen in intensity, which is accompanied by a rise of the loop voltage, and then the cyclotron radiation saturates soon after this sudden increase. Note that the emissivity of the electron cyclotron radiation is proportional to a mean perpendicular energy, which increases linearly in time in a plasma with anisotropic distribution function of electrons because of pitch-angle scattering. The abrupt increases in the loop voltage and cyclotron emission seem to result from an anomalous diffusion in perpendicular-velocity space which is driven by unstable plasma waves.[14] The signal decay time of the cyclotron emission is about 20 msec, which is very long compared to the electron energy confinement time. Figure 2(a) shows the relative changes in the loop voltage $\Delta V_1/V_{10}$, the cyclotron emission $\Delta I_c/I_{c0}$ and the hard-x-ray emission $\Delta H_x/H_{x0}$ versus the phase difference. The subscript 0 denotes the value for the discharge with no rf pulse and Δ the different value with the rf pulse. The experimental points were obtained from data just before the termination of the rf pulse having a width of $t_d = 10$ msec, during which the sudden increase in the cyclotron emission was not observed. In this case the decreased loop voltage relaxed in about 0.2 msec to its level for the discharge without the rf pulse.

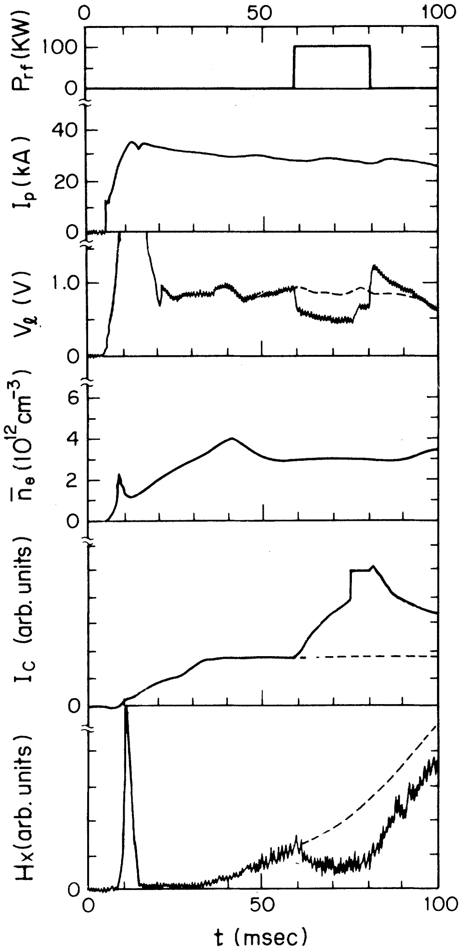

FIG. 1. Typical plasma shot: $B_t = 14$ kG and $\Delta\varphi = 90°$; the solid lines show the shot with the rf pulse and the dotted lines with no rf pulse.

The power spectrum versus the plasma refractive index (n_z) of the slow waves excited by an antenna in a boundary plasma is calculated from Brambilla's Grill theory[15] and the calculated results as a parameter of $\Delta\varphi$ are shown in Fig. 2(b). The effective linear Landau damping to heat the bulk electrons with $T_e = (250\text{ eV})/k$ would require $v_{pz}/v_e \gtrsim 3$ or $n_z \gtrsim 15$ [see Fig. 2(b)], which is far above the expected one where v_{pz} is the parallel phase velocity of the waves and v_e is the thermal velocity of electrons. Therefore, the decrease of the loop voltage seems to result from the generation of the rf-driven current carried by the suprathermal electrons rather than

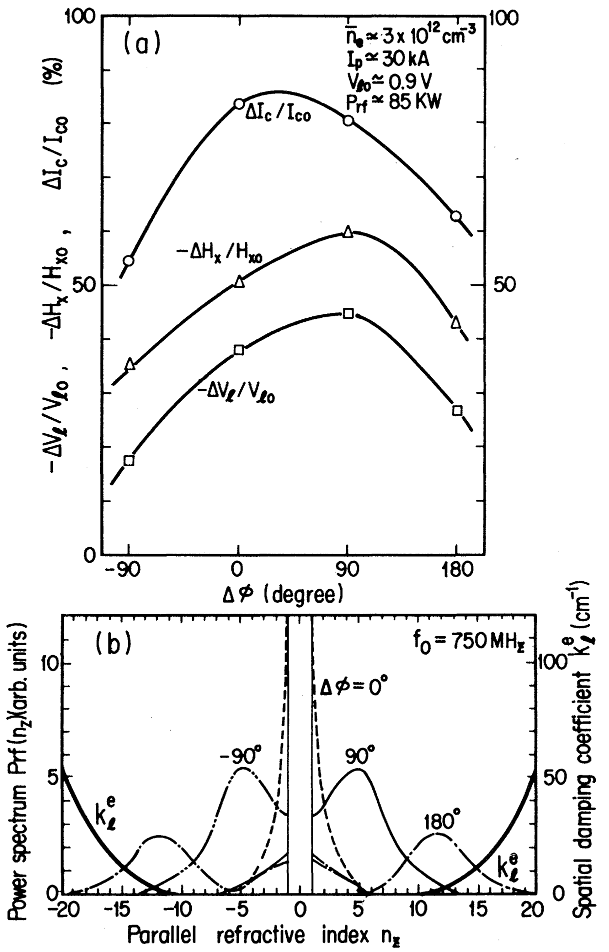

FIG. 2. (a) The relative changes in the loop voltage, cyclotron emission, and hard–x-ray emission vs the phase difference. (b) Calculated power spectrum of the slow waves excited by the four-waveguide antenna as a parameter of $\Delta\varphi$ and linear spatial damping coefficient at the central plasma vs n_z; a plus sign of n_z denotes the same direction with that of electron drift.

from the bulk electron heating. This is because the decay time of the total plasma current, $L/R \simeq 100$ msec (where L and R are plasma inductance and resistance, respectively), is so long compared with the duration of the rf pulse that the total current does not change during the rf pulse, although the inductive electric field is effectively shut off. The rf interaction with the suprathermal electrons is also supported by the time evolution of the cyclotron emission. As a result, the rf-driven current $I_{\rm rf}$ can be estimated as $I_{\rm rf} = I_p\,\Delta V_1/V_{10}$. A dc electric field produces suprathermal electrons with a velocity of $v > v_c = \{2(2+Z_{\rm eff})E_{\rm D}/E_0\}^{1/2}V_e$ in the steady state by balancing collisions or loss of high velocity electrons, $E_{\rm D}$ is the Drecier field and E_0 is the dc field, and thereby increases population in the tail of the distribution function.[14,16] When $v_c \lesssim v_{pz}$, the strong rf interaction with the suprathermal electrons is expected by resonant wave-particle interaction process. The present observation of the strong coupling between the rf waves and electrons is reasonable because $v_{pz}/v_c \approx 1$, provided that waves with the power spectrum shown in Fig. 2(b) are excited in the core plasma. However, it should be noted that the decrease of the hard–x-ray emission indicates no essential dc field is related to the generated current. It is also expected theoretically, from the viewpoint of the calculated power spectrum, that the waves excited at $\Delta\varphi = 90°$ should couple more effectively with the electrons producing the rf-driven current than the waves at $\Delta\varphi = -90°$. This agrees well with the experimental results shown in Fig. 2(a). This agreement strongly suggests that the waves having a power spectrum nearly equal to the calculated one are excited in the plasma. The relative changes of the loop voltage, the cyclotron emission, and the hard–x-ray emission as a function of the applied rf power for $\Delta\varphi = 90°$ are shown in Fig. 3. All relative changes are found to saturate at the applied rf power of 120 kW. When the applied rf power is 125 kW a rf-driven current of 15 kA is obtained.

The evolution of the electron distribution function integrated over the perpendicular velocity, in the presence of the rf waves with a finite spatial extent and the dc electric field, is given by

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial z} + \frac{eE_0}{m}\frac{\partial f}{\partial v} = \frac{\partial}{\partial v}D_{\rm rf}\frac{\partial f}{\partial v} + \left(\frac{\partial f}{\partial t}\right)_{rx}, \tag{1}$$

when z denotes the space variable along a magnetic field, $D_{\rm rf}$ is the quasilinear diffusion coefficient, $(\partial f/\partial t)_{rx}$ describes the relaxation due to the collision and the loss of electrons caused by imperfect magnetic surfaces. The diffusion coefficient due to the LH waves, propagating in a well-defined resonance cone such that the cross section of the cone $(L_z \times L_x)$ equals that of the antenna, can be calculated in a weak-turbulence theory as follows:

$$D_{\rm rf} = \left(\frac{e}{m}\right)^2 \frac{2\pi}{\epsilon_0\omega_0}\frac{\Delta v_{pz}}{v_{pz}}P_{\rm rf}(x)\left[\left(1+\frac{k_x^{\,2}}{k_z^{\,2}}\right)\left(1+\frac{\omega_{pe}^{\,2}}{\omega_{ce}^{\,2}}\right)v_{gx}L_zL_y\,\frac{x}{a}\right]^{-1}, \tag{2}$$

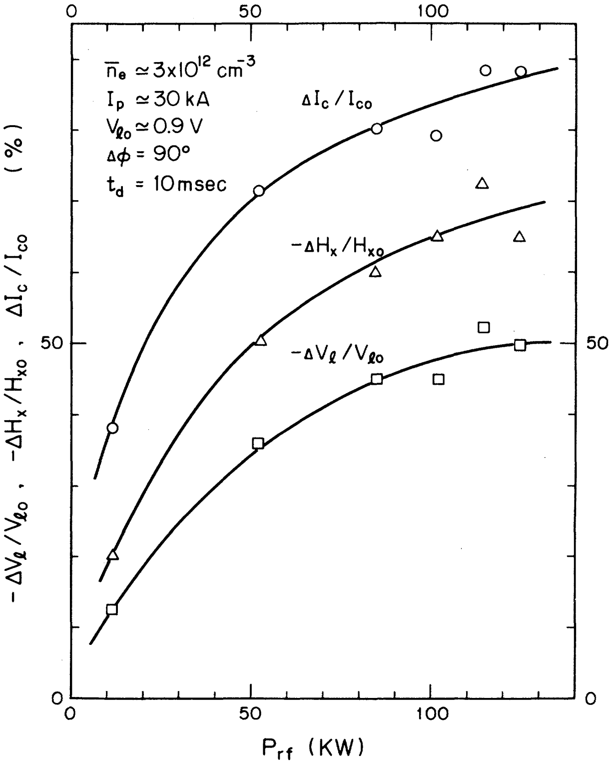

FIG. 3. The relative changes of the loop voltage, the cyclotron emission and the hard–x-ray emission as a function of the applied rf power.

where Δv_{pz} is the phase velocity range of the rf spectrum, $P_{\rm rf}(x)$ is the local rf power, v_{gx} is the group velocity and x/a is a cylindrical focusing factor. The quasilinear diffusion tends to flatten the distribution function in the region of the phase space that corresponds to resonant electron velocity, and thus generates the current. By balancing the collision and/or the loss against the quasilinear diffusion, the steady state is established. The diffusion coefficient $\hat{D}_{\rm rf}$ at which the quasilinear effect becomes important can be estimated from Eq. (1) in an order-of-magnitude sense as

$$\hat{D}_{\rm rf} \simeq \pi(\Delta v_{pz})^2 R_0 q/\tau_{rx} L_z, \tag{3}$$

where q is the safety factor of the tokamak and τ_{rx} is the relaxation time of the resonance electrons. With use of the plasma conditions corresponding to Fig. 3, the quasilinear effect should became important at power levels of 5–20 kW. Equation (3) approximately corresponds to $D_0 = 1$ in Ref. 5, which gives theoretically the rf-driven current of 30% of a saturation level ($D_0 \gg 1$). Taking account of the fraction of the irradiated rf power that satisfies the accessibility condition, we obtained good agreement between the theoretical prediction and the experimental result. In addition, perturbed-orbit effects in the diffusion and the dc field are found not to affect these estimates at these power levels.

The authors wish to thank Dr. Y. Tanaka for his useful suggestion and encouragement throughout the present work. They also appreciate the diagnostic group and the operations group of the JFT-2 tokamak for their important contributions throughout the experiments. They also appreciate Dr. S. Kunieda, Dr. H. Shirakata, Dr. Y. Obata, and Dr. S. Mori for their continuous encouragements.

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