Observation of Direct Electron Heating by the Fast Waves in the Lower-Hybrid Range of Frequencies in the JFT-2M Tokamak

T. Yamamoto, Y. Uesugi, H. Kawashima, K. Hoshino, H. Aikawa, S. Kasai, T. Kawakami, T. Kondoh,[a]
H. Maeda, T. Matsuda, H. Matsumoto, Y. Miura, M. Mori, K. Odajima, H. Ogawa, T. Ogawa, K. Ohasa,
H. Ohtsuka, S. Sengoku, T. Shoji, N. Suzuki, H. Tamai, T. Yamauchi, and I. Nakazawa[b]
Department of Thermonuclear Fusion Research, Naka Fusion Research Establishment,
Japan Atomic Energy Research Institute, Naka-gun, Ibaraki-ken, 319-11, Japan
(Received 2 February 1989)

It is observed that fast waves launched into an electron-cyclotron-heated plasma from a phased four-strip-line antenna array couple effectively with core electrons. This coupling produces enhanced electron cyclotron emission and a drop in the loop voltage. These effects depend on the phase difference between adjacent strip lines and on the electron density. An absorption efficiency of 20% is deduced under the conditions $v_{\mathrm{ph}}/v_{e0} \sim 3$ and $f_0/f_{\mathrm{LH}}(0) \sim 0.38$. The experimental results agree well with predictions based on electron Landau damping of fast waves.

PACS numbers: 52.40.Db, 52.50.Gj

In recent years, considerable attention has been focused on theoretical and experimental studies of lower-hybrid (LH) waves for plasma heating and/or current generation in tokamaks. These waves have been successfully employed to heat electrons and to drive plasma current via electron Landau damping (ELD) in a number of tokamaks.[1] Recently, current drive by LH waves (LHCD) in the JT-60 tokamak has been demonstrated with efficiencies close to the range expected for a steady-state tokamak reactor.[2] The LH waves, however, may not penetrate deeply into hot, fusion-grade plasmas because of strong ELD, an unfavorable accessibility condition or other effects near the edge of the plasma.

Fast waves (FW) in the LH range of frequencies could provide an alternative for heating and/or current generation in the central portion of reactor-grade plasmas.[3,4] In particular, current drive by FW (FWCD), based on the same mechanism as LHCD, is expected to have efficiencies as good as those obtained in LHCD experiments. Some experimental studies of FWCD in the frequency regime $f_{ci} \ll f_0 f_{\mathrm{LH}}(0)$, where $f_{\mathrm{LH}}(0)$ is the maximum LH resonance frequency in the plasma, have been done in toroidal devices[5,6] and tokamaks.[7-11] The experiments on the tokamaks,[8,9] however, have not conclusively shown that FWCD can be achieved by means of the ELD of the fast waves launched directly, possibly due to conversions of the fast waves to slow waves. In this Letter, we report the first experimental results using a 200-MHz fast wave launched from a phased four-strip-line antenna array into the JFT-2M tokamak. The results obtained for electron densities well above the LH resonance density show effective electron heating consistent with ELD of the fast waves.

The JFT-2M tokamak has a D-shaped vacuum vessel with a major radius $R_0 = 1.31$ m. The present experiments were performed in limiter-discharge plasmas with a minor radius of $a = 0.32$ m and an ellipticity of $\kappa = 1.4$. The plasma current was $I_p = 100$ kA and the toroidal magnetic field was $B_{t0} = 1.07$ T. The working gas was hydrogen. The target plasma was heated by electron cyclotron heating (ECH) with a frequency of 60 GHz, corresponding to the second-harmonic electron cyclotron

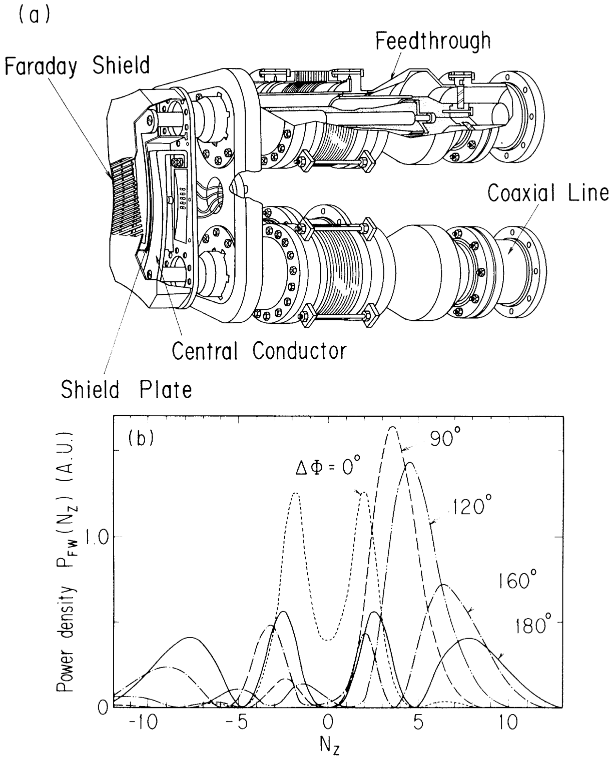

FIG. 1. (a) Phased four-strip-line antenna array with Faraday shield. (b) Calculated N_z power spectrum for the fast waves radiated by the array. The parameter $\Delta\Phi$ is the phase difference between adjacent antennas. N_z is the parallel refractive index.

frequency at the plasma center.

The FW system consists of four 200-MHz rf sources, each capable of supplying 180 kW for up to 0.5 sec through a circulator to one poloidal strip in an array of four-strip-line antennas equipped with a single Faraday shield, as shown in Fig. 1(a). The Faraday shield prevents direct excitation of the slow mode. The spacing between adjacent strip lines is 8 cm and the width of each strip line in the toroidal direction is 5 cm. The radiative length in the poloidal direction of the antenna is 18 cm. The phase difference, $\Delta\Phi$, between adjacent antennas is adjusted independently by a phase shifter in the low-power circuit and then monitored by pickup coils placed behind slits in the return plate. The impedance of each line is matched using double stub tuners. The power spectrum of the radiated fast waves, calculated in a two-dimensional semi-infinite plasma model[12] using the surface-plasma impedance evaluated in Ref. 13, is shown with $\Delta\Phi$ as a parameter in Fig. 1(b). In the calculation, we assume an electron density profile given by $n_e(r)=(1.5\times10^{19}\ \mathrm{m}^{-3})[1-(r/a)^2]^{1.5}$ and set $N_y=0$, where N_y is the refractive index of the waves in the poloidal direction. Each antenna is fed with constant current and the total radiated power is kept constant.

The typical time behavior of the relevant plasma parameters for two discharges is shown in Fig. 2(a). The solid lines in the figure indicate the results of FW combined with ECH and the dashed lines indicate those obtained without the FW pulse. The radiated FW and ECH powers were $P_{\mathrm{FW}}=300$ kW and $P_{\mathrm{ECH}}=180$ kW, respectively. The value of $\Delta\Phi$ was set at 160°, which yields a spectrum having a peak at $N_z=6.5$ and a width of $\Delta N_z\sim4$. The line-averaged density $\bar{n}_e$ was kept constant at $\bar{n}_e=0.95\times10^{19}\ \mathrm{m}^{-3}$ by feedback control during the rf pulses for both cases. The present plasma parameters yield the range of 1.06 to 15 for the accessible N_z at the plasma center and $r_{\mathrm{LH}}/a=0.93$ for the radial position of the LH resonance layer at 200 MHz. When ECH power is applied, the central electron temperature rises to 1.5 keV from 0.6 keV. With application of FW power during the ECH pulse, an appreciable further drop in the loop voltage ΔV_l, and substantially enhanced electron cyclotron emissions (ECE) are observed. The ECE signals for the extraordinary mode were detected by a radiometer. The signal at 50.4 GHz was received by a horn antenna placed outside the torus in its midplane, and those at 86 and 90 GHz by an antenna placed inside the torus. The radiation temperature deduced from ECE was calibrated using the Thomson-scattering diagnostic. Note that the frequency 50.4 GHz corresponds to the second harmonic at $r/a=0.78$, while 86 and 90 GHz correspond to the third harmonic at $r/a=0.19$ and 0.0, respectively. Evidence of internal sawtooth oscillations is observed in ECE signals at 86 and 90 GHz in both cases. The FW power enhances the sawtooth oscillation and increases their period by about 50%. The FW is also found to produce an increase of 0.5 kJ in the stored plasma energy, estimated from the diamagnetic measurement W_{dia}. The increase in the stored energy and the drop in the loop voltage imply an absorption efficiency of 20%, assuming no change of en-

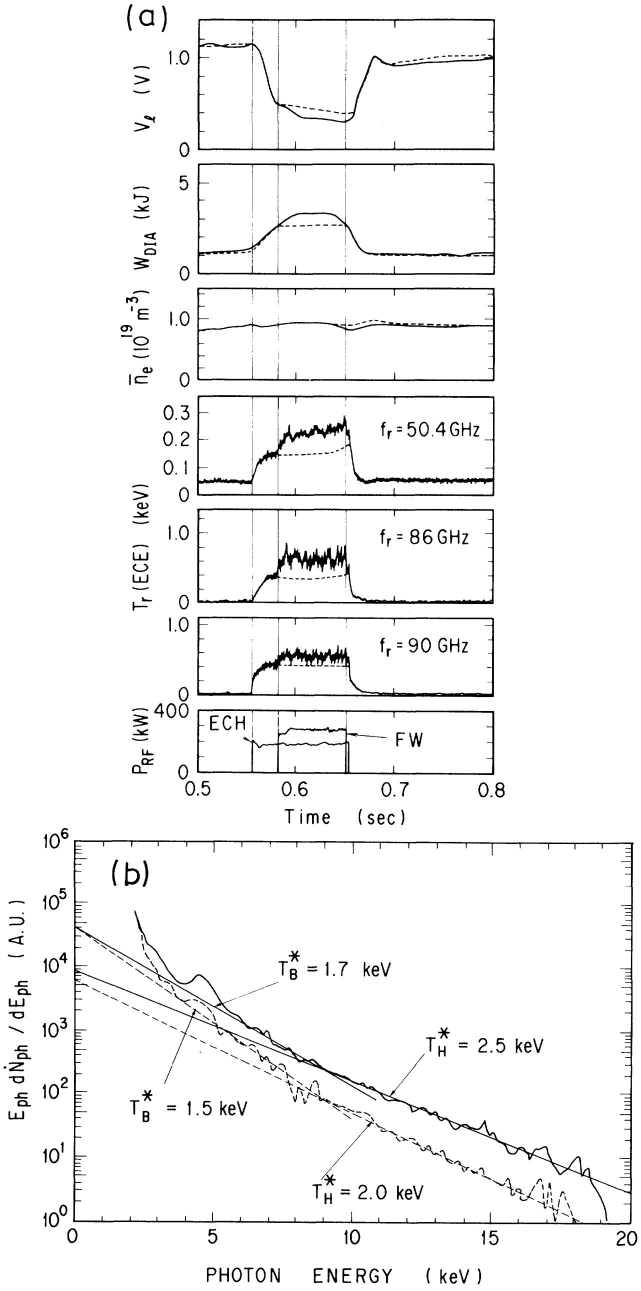

FIG. 2. (a) Time evolution of loop voltage, V_l, stored plasma energy, W_{dia}, line-averaged electron density, $\bar{n}_e$, and ECE radiation temperature, T_r, for two typical shots with and without (solid and dashed lines) FW power during the ECH pulse. $I_p=100$ kA, $B_{t0}=1.07$ T, and $\Delta\Phi=160°$. (b) Soft-x-ray energy spectra with and without (solid and dashed lines, respectively) FW power during the ECH pulse. The plasma conditions are the same as in (a), except that $P_{\mathrm{FW}}=270$ kW.

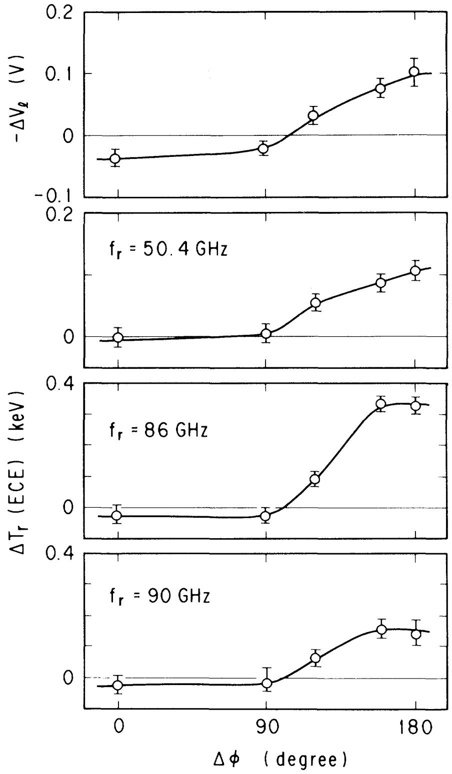

FIG. 3. Dependence of the change in loop voltage, ΔV_l, and in the ECE radiation temperature, ΔT_r, on the phase difference between adjacent antennas. The plasma conditions are the same as those in Fig. 2(a), except that $P_{\rm FW}=275\pm25$ kW.

ergy confinement time during the rf pulses.

The energy spectra of the soft-x-ray radiation obtained under the same conditions as those of Fig. 2(a), except that $P_{\rm FW}=270$ kW, are shown in Fig. 2(b). The radiation parallel to the drift of the current-carrying electrons in the midplane was measured by an intrinsic germanium detector with a pulse-height analysis system. The data for ten identical shots were superposed. The solid lines indicate the results of the combined FW and ECH pulses and the dashed lines indicate those obtained without the FW pulse. The ECH is seen to produce a plasma characterized approximately by two Maxwellian electron distributions with different temperatures for bulk and tail electrons. The temperature of the bulk component was somewhat higher than the central electron temperature measured using Thomson scattering. Both components are seen to be heated effectively by the FW. Note that the calculated power spectrum of the fast waves couples through Landau resonance to electrons with energies in the range of 3.5–10 keV. These results imply that the FW interacts with resonant electrons which transfer the excess energy to central plasma electrons. In the absence of ECH, we have observed no appreciable heating of electrons under conditions otherwise identical to those mentioned above.

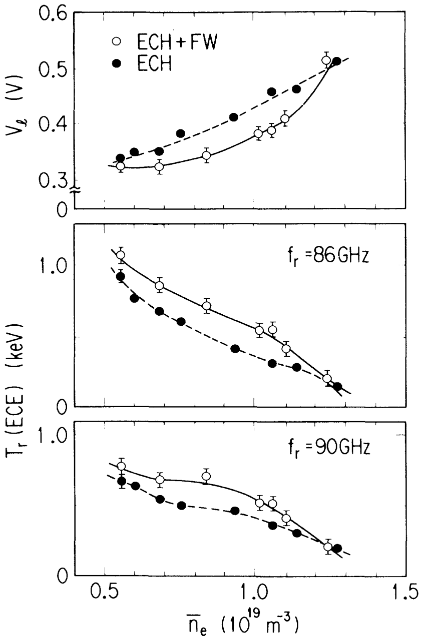

FIG. 4. Density dependence of loop voltage and ECE radiation temperature with and without (open and solid circles, respectively) FW power during ECH pulse. $\Delta\Phi=160°$ and $P_{\rm FW}=210\pm20$ kW.

Figure 3 shows the changes in the loop voltage and ECE as functions of the phase difference between the antennas. The data were obtained under nearly the same conditions as those of Fig. 2(a), except for the phasing. It is found that fast waves launched with $\Delta\Phi \geqq 120°$, corresponding to $v_{pz}/v_{e0} \leqq 3.7$ (where v_{pz} is the phase velocity parallel to the toroidal magnetic field for the dominant fast waves and v_{e0} is the thermal velocity of the central electrons), interact appreciably with plasma electrons, producing a drop in the loop voltage. The stronger enhancement of ECE at 86 GHz (as compared with that observed at 90 GHz) is ascribed to down shifting of the ECE from energetic electrons at the plasma center. The energetic electrons also enhance the optical depth of ECE and then increase the radiation temperature. The optical depth for third-harmonic emissions from the central plasma is evaluated $\tau_{\rm opt}\sim0.1$ for the Maxwellian electrons. The observed increase in the radiation temperature is inferred to be contributed from the energetic electrons produced by the fast waves. On the other hand, it is seen that waves with $\Delta\Phi \leqq 90°$, corresponding to $v_{pz}/v_{e0} \geqq 4.6$, do not couple appreciably with electrons, leading instead to the plasma cooling with a resulting increase in loop voltage. A substantially enhanced inward flux of impurities has also been observed during the FW pulse. The lack of coupling for $\Delta\Phi \leqq 90°$ shows that the problem of the "spectral gap," where many very energetic electrons are created although the spectrum launched at the plasma edge is not slow enough to interact with a substantial number of resonant electrons, does not exist here, in contrast to the LHCD.

The density dependences of the loop voltage and ECE when ECH is applied with and without FW power are shown in Fig. 4. The data were obtained for $P_{FW}=210 \pm 20$ kW and with $\Delta\Phi = 160°$. In both cases, the temperature decreases with increasing electron density and the resulting loop voltage increases. It should be noted that the drop in the loop voltage and the increase in ECE due to application of the FW pulse are most pronounced near $n_e = 1.0 \times 10^{19}$ m^{-3}. At the lower densities, the enhancement of ECE is not as large, even at relatively high temperatures. In addition, no appreciable drop in the loop voltage is observed at $\bar{n}_e = 0.55 \times 10^{19}$ m^{-3}. At $\bar{n}_e = 1.2 \times 10^{19}$ m^{-3}, there are no drops in the loop voltage and no enhanced ECE. These heating results are consistent with the theoretical dependence of ELD of the fast waves on the electron density and temperature.

We have calculated the single pass absorption of the fast waves and the associated rf-driven current for the present experimental conditions. In the calculation, the wave equation, coupled with the one-dimensional quasilinear Fokker-Planck equation taking into account perpendicular dynamics,[14] has been solved in the WKB approximation for cylindrical geometry. A ray-tracing calculation indicates no significant spatial variation of N_z and dominant electron Landau damping rather than transit-time magnetic pumping and ion cyclotron higher-harmonic dampings under the present experimental conditions. The wave spectrum calculated for radiation from a four-antenna array, as shown in Fig. 1(b), was used. The results indicate an absorption efficiency of 10% for plasma conditions corresponding to Fig. 2. The rf-driven current is predicted to be 3 kA. The calculation also indicates that the absorption of the waves launched with $\Delta\Phi \leqq 90°$ is less than 3% for $T_{e0} \leqq 2$ keV. This agrees well with the experimental results obtained.

In summary, we have observed direct electron heating by fast waves in the lower-hybrid range of frequencies launched by a phased four-antenna array into the JFT-2M tokamak. The heating depends on the phasing of the antennas and on the plasma density in a way consistent with electron Landau damping. These results suggest that the antenna array used can control the parallel wave-number spectrum of the excited fast waves. Therefore, unidirectionally propagating waves excited by such an antenna array can be expected to be efficient in generating current drive if the electron temperature is more than 3 keV, although no clear FWCD has been observed in the present experiments. In addition, the substantial absorption of fast waves might be efficient in producing current drive in the reactor-grade plasmas by the mechanism of helicity injection as recently proposed by Chan and Ohkawa.[15]

We would like to thank the JFT-2M operating and heating group teams, headed by K. Suzuki, for their expert support of this work, and Dr. R. Neufeld for his critical reading of the manuscript. We are grateful for continued support from Dr. S. Shimamoto, Dr. M. Tanaka, Dr. M. Yoshikawa, and Dr. S. Mori.

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[a] On leave from University of Tsukuba, Ibaraki, Japan.

[b] On leave from Mitsubishi Electric Co., Tokyo, Japan.

[1] N. J. Fisch, Rev. Mod. Phys. **59**, 175 (1987).

[2] T. Imai *et al.*, Nucl. Fusion **28**, 1341 (1988).

[3] K. L. Wong *et al.*, Nucl. Fusion **23**, 805 (1983).

[4] D. A. Ehst *et al.*, Nucl. Fusion **26**, 461 (1986).

[5] J. Goree *et al.*, Phys. Rev. Lett. **55**, 1669 (1985).

[6] R. McWilliams and R. C. Platt, Phys. Rev. Lett. **56**, 835 (1986).

[7] R. J. Taylor *et al.*, in *Proceedings of the Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, London, 1984* (International Atomic Energy Agency, Vienna, 1985), Vol. 1, p. 581.

[8] K. Ohkubo *et al.*, Phys. Rev. Lett. **56**, 2040 (1986).

[9] R. Andou *et al.*, Nucl. Fusion **26**, 1619 (1986).

[10] S. Bernabei *et al.*, in *Proceedings of the Eleventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, 1986* (International Atomic Energy Agency, Vienna, 1987), Vol. 1, p. 503.

[11] T. Yamamoto *et al.*, in Ref. 10, p. 545.

[12] R. R. Weynants *et al.*, in *Proceedings of the Second Joint Grenoble–Varenna International Symposium on Heating in Toroidal Plasmas, 1980* (Commission of the European Communities, Brussels, 1980), Vol. 1, p. 487.

[13] V. L. Vdovin, Nucl. Fusion **23**, 1435 (1983).

[14] V. Fuchs *et al.*, Phys. Fluids **28**, 3619 (1985).

[15] V. S. Chan and T. Ohkawa, General Atomics Report No. GA-A19406, 1988 (unpublished).