Interaction of Lower Hybrid Wave with Fast Ions Injected by Neutral Beam on the JT-60 Tokamak

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The acceleration of beam ions due to their interaction with lower hybrid (LH) waves is investigated. The critical coupling density, above which the LH power is absorbed mostly by ions rather than electrons, is found to depend strongly on the LH frequency but not on the refractive index parallel to the toroidal magnetic field. These dependences are in good agreement with the predictions of a simple, clear theory based on a dispersion relation in the electrostatic cold-plasma approximation.

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In order to establish steady-state operation in a tokamak reactor, the noninductive current drive method with radio-frequency waves has been investigated.[1] The lower hybrid (LH) wave, which is one of the electrostatic waves in a plasma, is considered to be an efficient way to drive plasma current off axis, especially when complemented by neutral-beam current drive in the core. It is known that the LH wave can interact with both electrons and ions,[2–4] depending on the background plasma density, and changing plasma conditions may change the effectiveness of current drive. Also, fusion α particles or reionized high-energy neutral-beam (NB) ions affect the LH wave interaction with electrons and ions. Investigations of particle acceleration by LH waves[5,6] show the presence of a critical density, above which the LH wave couples predominantly to ions rather than electrons. A theoretical study of the LH wave absorption by α particles in a reactor[7] has also been done.

In this Letter, we report an experimental result of LH damping to charged particles and the good agreement between high-energy ion characteristics measured by a charge-exchange neutral-particle mass-energy (CX) analyzer and the prediction from theory.

The CX measurement system on JT-60[8] consists of four analyzers: three perpendicular and one tangential. One of the perpendicular ones views the NB lines from the top of the torus, and is therefore able to measure the ion energy distribution at the core by an application of active CX methods.[9,10] LH power was injected from a multijunction-type launcher consisting of 24 (toroidal) by 4 (poloidal) phased-array waveguides.[11] The waves were produced by klystrons whose frequency is able to be varied from 1.74 to 2.23 GHz. The peak $N_\parallel$ (refractive index parallel to the toroidal magnetic field) was varied from 1.2 to 4.0, with $\Delta N_\parallel \sim 0.5$ at a frequency of 2.0 GHz.

Experiments were carried out in hydrogen plasmas with a near-circular limiter configuration having the following parameters: plasma current $I_p = 1.5$ MA, toroidal magnetic field $B_T = 4.5$ T, plasma major radius $R_p = 3.04$ m, and plasma minor radius $a_p = 0.89$ m. The LH wave frequency was varied from 1.74 to 2.23 GHz at a fixed $N_\parallel$ of 2.2 in order to investigate the frequency dependence of the critical density for acceleration of hydrogen beam ions by the LH wave. Figure 1(a) shows wave forms for three cases of simultaneous injection of LH and NB with LH frequencies of 1.74, 2.0, and 2.23 GHz and beam energy of 65 keV. Since high-power NB injection would have raised plasma density and made accurate measurements of the acceleration phenomena difficult, only the NB unit whose beam line was viewed by the CX analyzer was used. The top traces show the time evolutions of line-integrated electron density and NB power $P_{\rm NBI}$. The electron density was raised at a constant rate by a feedback control system. The second set shows, on a logarithmic scale, the CX flux intensities F_i at 150 keV for the three LH frequencies. The flux intensities show a clear onset of acceleration above a critical density. Accompanying the increase of accelerated ions by LH is a steep decrease in the power absorbed by electrons, as shown in the third plot. Here, the vertical axis is the product of the intensity of nonthermal electron cyclotron emission (ECE) at $1.5\omega_{ce}$ and the line-integrated density. Data for the 2.23-GHz case are absent because of an ECE system error. Note that the differences in injected LH power for the three cases, as shown in the bottom traces, did not influence the essential characteristics. The typical ion energy distributions at $\bar{n}_e = 1.8\times10^{19}$ m^{-3} for the three cases are shown in Fig. 1(b). In the case of 1.74 GHz, shown with solid circles, beam acceleration up to 200 keV is evident. On the other hand, the tail slope of the 2.23-GHz case, shown with solid triangles, is similar to the case of NB only. The ion acceleration must be due to absorption of the LH wave because rf probes did not detect parametric decay waves in these discharges.

The coupling condition between high-energy particles like α particles and LH[7] is

$$E_\alpha = \tfrac{1}{2} m_\alpha (\omega/k)^2_{\rm LH} \le E_0 ,$$

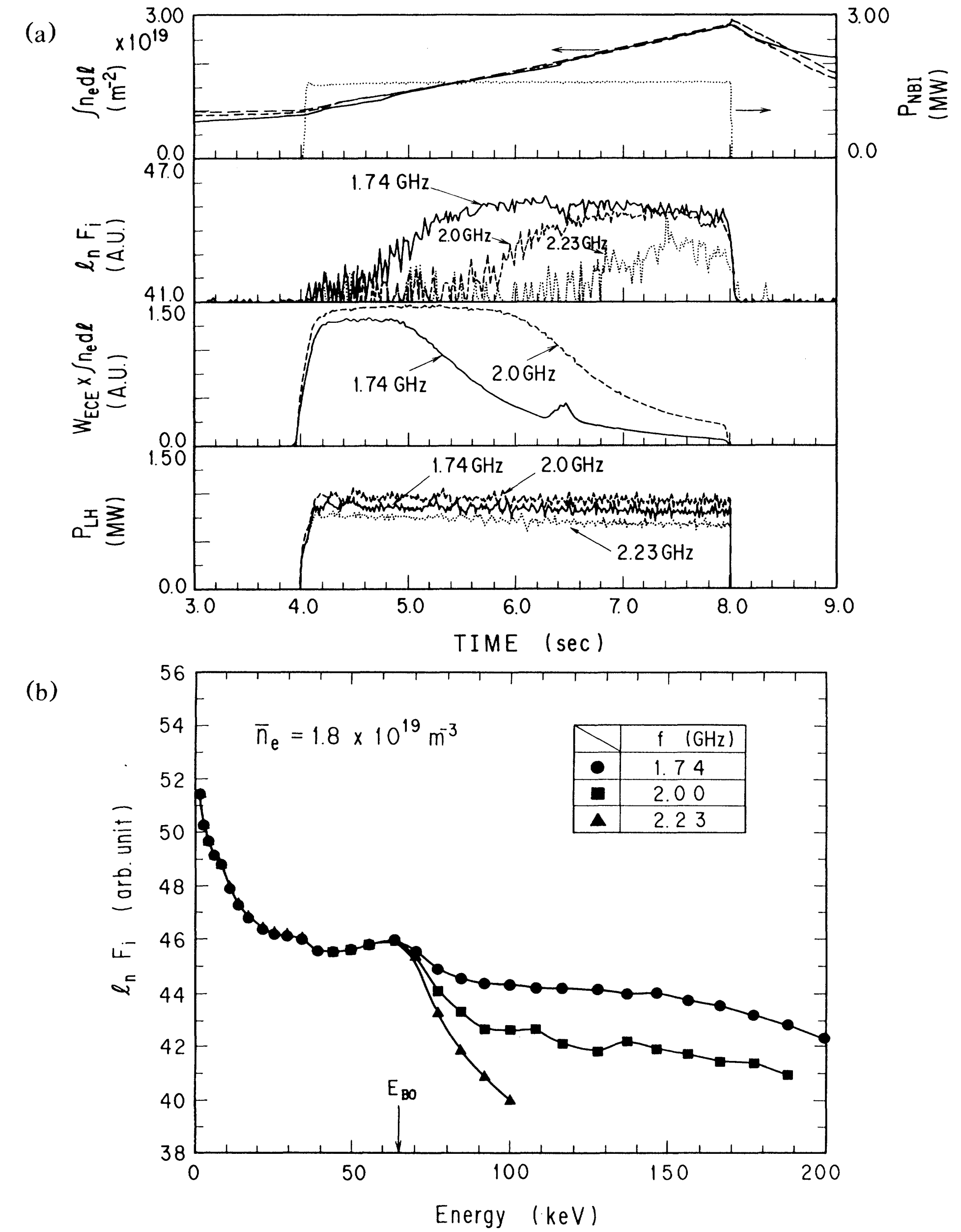

FIG. 1. (a) Time evolutions of line density, injected neutral beam power, CX flux intensity, product of $1.5\omega_{ce}$ wave and line density, and injected LH wave power. (b) Typical ion energy distributions measured with the CX analyzer. An arrow indicates energy of injected NB.

where m_α is the α-particle mass, $(\omega/k)_{\rm LH}$ is the phase velocity of LH, and E_0 is the birth energy of α particles ($E_0=3.5$ MeV). This condition is true if the α coupling is stronger than electron coupling in the entire plasma. However, if the electron coupling competes with α coupling or both $\omega/k_\parallel$ and $\omega/k_\perp$ are far from the electron thermal velocity and α (or fast ion) velocity, respectively, the above equation is not relevant. It is necessary to introduce a new criterion to predict the interaction.

We expect that the characteristics of the beam acceleration obey the following equation. In the electrostatic cold-plasma approximation, the LH wave satisfies a dispersion relation given by

$$\left(\frac{k_\parallel}{k_\perp}\right)^2=\left(\frac{N_\parallel}{N_\perp}\right)^2=\left(\frac{f}{f_{pe}}\right)^2+\left(\frac{f}{f_{ce}}\right)^2-\left(\frac{f_{pi}}{f_{pe}}\right)^2, \quad (1)$$

where $k_\parallel$ and $k_\perp$ are the wave numbers parallel and perpendicular to the toroidal magnetic field, and f, f_{pe}, f_{ce}, and f_{pi} are the pump frequency and the electron plasma, electron gyro, and ion plasma frequencies, respectively. Here, since the LH wave accelerates electrons and ions in parallel and perpendicular directions, respectively, we define two measures, δ_e and δ_i, which indicate absorption rates of LH power[12,13] by electrons and ions, as

$$\delta_e \equiv (F_\delta v_e / v_\parallel)^2, \quad \delta_i \equiv (v_B / v_\perp)^2,$$

where v_e and v_B are electron thermal and beam ion velocities, $v_\parallel$ and $v_\perp$ are LH phase velocities parallel and perpendicular to the toroidal magnetic field, and F_δ is a constant value. Moreover, we define a ratio between electron and ion coupling strength as

$$\delta \equiv \frac{\delta_i}{\delta_e} = \left(\frac{1}{F_\delta}\frac{v_B}{v_e}\right)^2 \left(\frac{N_\perp}{N_\parallel}\right)^2 .$$

Then, we rewrite Eq. (1) by using δ as

$$\left(\frac{f}{f_{pe}}\right)^2 = \frac{m_e E_B}{F_\delta^2 m_p T_e \delta} - \left(\frac{f}{f_{ce}}\right)^2 + \left(\frac{f_{pi}}{f_{pe}}\right)^2, \qquad (2)$$

where E_B is the beam energy, T_e is the electron temperature, and m_e and m_p are the masses of the electron and the proton as beam species. To find the critical density n_e^c at which the electron heating and ion coupling become equal, we set $\delta = 1$ in Eq. (2), obtaining

$$n_e^c = \frac{2.28 f_G^2}{E_B / F_\delta^2 A_B T_e + \gamma - 2.34 (f_G / B_T)^2}, \qquad (3)$$

where n_e^c is in 10^{19} m^{-3}, f_G is the LH wave frequency in GHz, E_B and T_e are in eV, B_T is in tesla, A_B is the atomic mass of the injected beam species, and γ is defined as

$$\gamma \equiv \frac{1}{\bar{n}_e} \sum_i \frac{Z_i^2 \bar{n}_i}{A_i} .$$

$\bar{n}_e$ and $\bar{n}_i$ are electron and ion densities, in units of 10^{19} m^{-3}, and the summation is performed over ion species i with charge state Z_i and atomic mass A_i.

We calculated the dependence on LH frequency of the critical electron density with typical JT-60 experimental parameters of $E_{B0} = 65$ keV, $T_e = 3$ keV, $B_T = 4.5$ T, and $\gamma = 0.8$ when $Z_{\text{eff}} = 3$, assuming carbon as the dominant impurity. Since collisions between injected NB and bulk ions always generate ions with energies higher than the injected NB energy, called the high-energy ion tail, we must take account of a beam spread ΔE. We used a ΔE of 10 keV in the calculation, since the flux of fast ions become appreciable from $E_{B0} + 10$ keV. Using $E_B = E_{B0} + \Delta E$, a satisfactory result was obtained at $F_\delta = 2.75$, which is a reasonable value compared with the theoretical value from quasilinear Landau damping. Figure 2 shows the calculation result with a solid line and the experimental data with solid circles. They are in

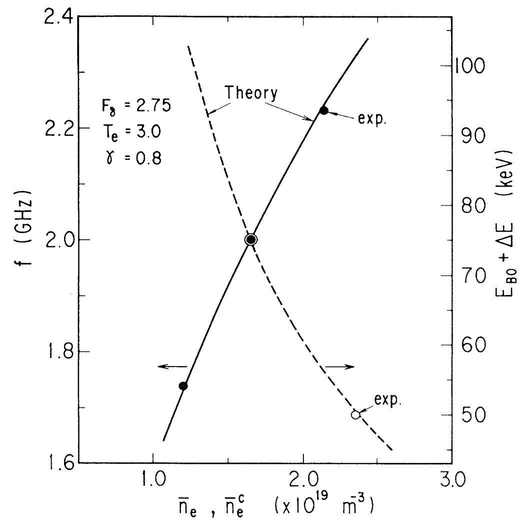

FIG. 2. Comparison of experimental data with calculation for the critical density of the beam acceleration. Solid line and solid circles are the calculation result and experimental data for frequency dependence, respectively. Dashed line and open circles are the calculation result and experimental data for beam-energy dependence, respectively.

good agreement. Here, we express critical density as an average value $\bar{n}_e^c$. Next, in order to study the dependence on beam energy, we carried out an experiment with NB of $E_{B0} = 40$ keV, LH wave of $f = 2.0$ GHz and $N_\parallel = 2.2$, and the same B_T and configuration as in the previous experiment. The electron density when accelerated ions of 120 keV were detected was 2.35×10^{19} m^{-3} as shown in Fig. 2 with an open circle. The correlation between the generation of high-energy ions and the reduction in the product of the ECE wave intensity and the electron density was the same as that in the case of 65-keV injection. The dependence on beam energy of the critical density, which was calculated from Eq. (3) using the previous parameters and shown with a dashed line in Fig. 2, is also consistent with the experimental data.

Equation (3) predicts that the critical density does not depend on $N_\parallel$, and this was also verified experimentally. The plasma parameters were the same as the first experiment, except that the LH frequency was fixed at 2.0 GHz. $N_\parallel$ was varied from 1.3 to 2.8, by changing the phase difference from 120° to 270°. No significant differences in the critical density for the generation of high-energy ions are seen among three $N_\parallel$ cases, as predicted from Eq. (3). We characterized an enhancement of the high-energy ion flux by the tail temperature T_i^{tail} which was calculated by taking the slope of the tail energy distribution at energies above the injected beam energy, as measured by the CX analyzer. Figure 3 shows the dependence of the tail temperature on the density for the three $N_\parallel$ cases at 2.0 GHz. This shows the same density dependence as Fig. 2 in spite of the variation of $N_\parallel$, al-

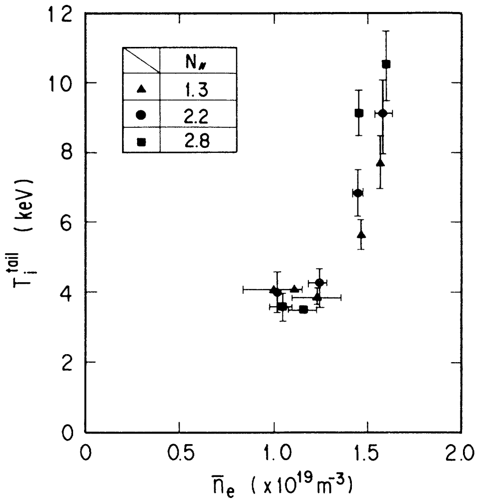

FIG. 3. Density dependence of the tail temperature which is calculated by taking the slope of the tail energy distribution at energies above the injected beam energy, as measured by the CX analyzer.

though the tendency that larger-$N_\parallel$ waves are able to generate a higher tail temperature at the same density is observed. Our experimental observation clarifies the independence of the critical density on the peak $N_\parallel$ value. Almost complete absorption of the LH power is observed even in the case of $\delta_e \ll 1$ and $\delta_i \ll 1$. This indicates that $N_\parallel$ must be up-shifted in such cases, since $\delta_e \sim 1$ or $\delta_i \sim 1$ is necessary for absorption.

In summary, beam acceleration by LH waves was studied in limiter plasmas on JT-60. We introduced a new criterion of the critical density for coupling to beam ions. It was demonstrated that the critical density was in good agreement with the prediction from the theory. The results can clearly predict the interaction of α particles or fast ions with LH waves in future tokamaks.

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