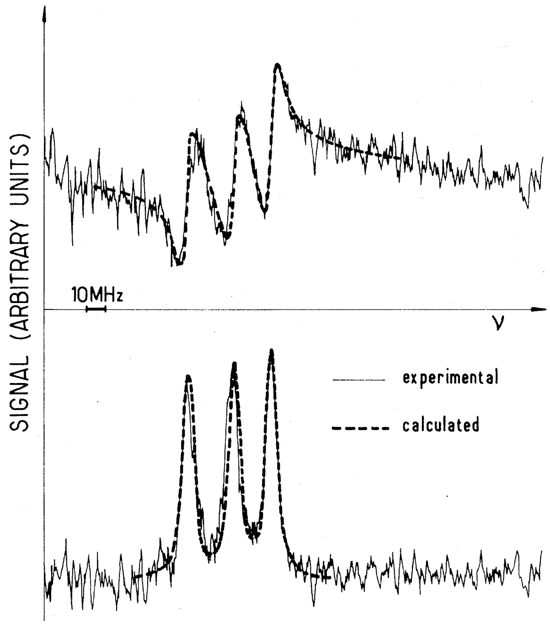

FIG. 3. Saturation spectra of three hyperfine components of an iodine line near 5900 Å: upper part, saturated-dispersion spectrum; lower part, saturated-absorption spectrum. Experimental conditions: angle between the beams, 13 mrad; frequency sweep rate, 0.9 MHz/sec; time constant, 0.1 sec.

in great agreement with the experimental data.

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Plasma Heating by Lower-Hybrid Parametric Instability Pumped by an Electron Beam

K. Yatsui and T. Imai

Department of Electrical Engineering, Osaka University, Toyonaka, Osaka 560, Japan

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We study experimentally the interaction of an electron beam modulated near the lower-hybrid frequency with a longitudinally magnetized inhomogeneous plasma. At high levels of beam modulation above a certain threshold, the beam pumps the parametric decay instability into the lower-hybrid wave and ion-acoustic wave, and correspondingly plasma heating takes place rapidly. The instability threshold is determined in a parameter space. These results are compared with theory, and reasonable agreement is obtained.

The interaction of a modulated electron beam with a longitudinally magnetized plasma is one of the most familiar themes in plasma physics. By use of the collective and internal interaction, several linear and nonlinear phenomena have been studied. In particular, the interaction near the lower-hybrid frequency ω_{LH} is of considerable interest from the viewpoint of plasma heating, since the electrostatic instabilities at $\omega \simeq \omega_{LH}$ have large growth rates together with a high level of saturation.[1] In fact, rapid plasma heating has been reported in such a beam-plasma system.[2,3] No established theory, however, has been made for the heating mechanism. Modulating the beam by a high-power transmitter, we have proposed recently[4,5] that the energetic ion production above appears to be due to the lower-hybrid parametric mode conversion that is pumped by the beam, rather than due to beam-plasma instabilities or linear mode conversion. In this Letter, we wish to present in detail these experimental results on the nonlinear interaction in the modulated electron-beam–plasma system.

The experiments were done in the Osaka University B-1 and B-2 linear devices.[6] The cylindrical vacuum chamber (stainless steel) of the former was 10 cm in i.d. and 85 cm long, and that of the latter was 32 cm in i.d. and 23 cm long in the central part, while it was 13 cm in i.d. and 120 cm long in the outer part. The electron beam, obtained by a magnetron injection gun of perveance $G \simeq 10^{-5}$, was modulated by a 1-kW cw transmitter, and injected into a magnetic mirror. Here, the transmitter output was connected in series to the dc power supply of the electron gun. The mirror ratios were $R_m = 1.1$ and 2.2 for the B-1 and B-2 devices, respectively. The electron beam injected produces a low-density argon plasma. In addition to beam injection, plasma could also be generated by a microwave discharge (2.45 GHz, 1 kW) in the B-2 device. Typical beam and plasma parameters were beam voltage $V_b = 0.1-1.0$ kV, beam current $I_b < 400$ mA, beam radius $r_b \simeq 8$ mm, argon pressure $p = (1-7)\times 10^{-5}$ Torr, plasma density $n = (0.2-6)\times 10^9$ cm^{-3}, plasma radius (half-width of radial density distribution) $r_p < 3$ cm, magnetic field strength (at the midplane of the machine) $B_0 = 0.3-1.5$ kG, electron temperature $T_{e\parallel}$ (parallel to $\vec{B}_0$) = 5–15 eV, and ion temperature $T_{i\perp}$ (perpendicular to $\vec{B}_0$) = 4–10 eV. The temperatures above are those in the absence of beam modulation.

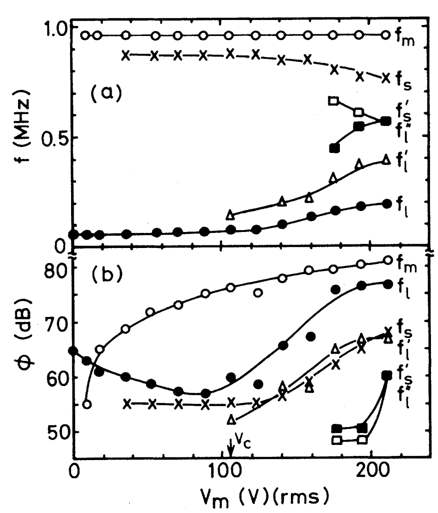

FIG. 1. (a) Oscillation frequency f and (b) amplitude φ versus modulation voltage of transmitter V_m with $p = 3.4\times 10^{-5}$ Torr, $V_b = 300$ V, and $B_0 = 830$ G. The data were taken in the B-1 device. Upper sideband waves to the f_m mode were omitted for simplicity.

Typical experimental results are shown in Fig. 1, where (a) the frequency and (b) the amplitude of oscillations are plotted versus modulation voltage of the transmitter V_m. In the absence of beam modulation, we see the presence of low-frequency oscillation at ~ 60 kHz (f_l mode), which is almost twice the ion cyclotron frequency f_{ci} ($\simeq 32$ kHz). Since there exists a crossfield current under this condition,[6,7] we guess that the f_l mode appears to be the crossfield-current–driven ion-acoustic wave propagating nearly perpendicular to $\vec{B}_0$. In addition, density measurement yields $n \simeq 7.8\times 10^8$ cm^{-3} for this case. Thus, we estimate that the electron cyclotron frequency f_{ce} ($\simeq 2.3$ GHz) is much larger than the electron plasma frequency f_{pe} ($\simeq 0.25$ GHz); hence, the experiment corresponds to the low-density case, $f_{ce}^2 \gg f_{pe}^2$. For this case, the lower-hybrid frequency $f_{\rm LH}$ should be approximated by the ion plasma frequency f_{pi} ($\simeq 0.92$ MHz). Here, we apply a low-frequency *radial* electric field by modulating the electron beam at $f_m = 0.96$ MHz ($\gtrsim f_{\rm LH}$). If we increase the modulation voltage, the f_l mode first starts to be suppressed. In addition, there appears the lower sideband (f_s) to the f_m mode. With the further increase in V_m above a certain threshold voltage V_c, strong low-frequency turbulence tends to grow; namely, at $V_m > V_c \simeq 105$ V, these wave amplitudes strongly grow, and there appear frequency shifts of the modes excited.[4,5] The frequency conservation law, $f_m = f_s + f_l$, is seen to be satisfied.

Figure 2(a) shows the ion and electron temperatures versus modulation frequency. As seen here, plasma heating resonantly takes place at $f_m \simeq 1.1-1.3$ MHz. Since we know $f_{\rm LH} \simeq 0.92$ MHz, the resonant heating above appears at ~ (1.2–1.4) $\times f_{\rm LH}$. Figure 2(b) shows the ion and electron temperatures versus modulation voltage for the resonance condition. In the absence of beam modulation, we see $T_{i\perp} \simeq 15$ eV and $T_{e\parallel} \simeq 9$ eV. Such a considerable ion heating seems to be due to the crossfield current.[6] As the modulation voltage increases, ions and electrons come to be heated rapidly. At high levels of beam modulation, where low-frequency turbulence has developed strongly (cf. Fig. 1), substantial ion and electron heating takes place up to $T_{i\perp} \simeq 45$ eV and $T_{e\parallel} \simeq 25$ eV. Though argon ions are estimated to have gyro orbits comparable to or larger than the plasma size in such a hot-ion plasma, these hot ions could be confined radially by a negative plasma potential.[6]

Next we have measured the instability thresh-

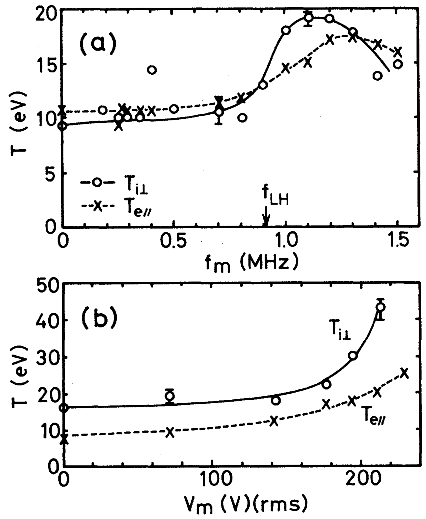

FIG. 2. (a) Ion ($T_{i\perp}$) and electron ($T_{e\parallel}$) temperatures versus modulation frequency f_m with $p=3.3\times10^{-5}$ Torr, $V_b=300$ V, and $V_m(\text{rms})=142$ V. (b) Ion ($T_{i\perp}$) and electron ($T_{e\parallel}$) temperatures versus modulation voltage for the resonance condition with $p=3.2\times10^{-5}$ Torr, $V_b=400$ V, $B_0=830$ G, and $f_m=960$ kHz. The two results above were taken in the B-1 device.

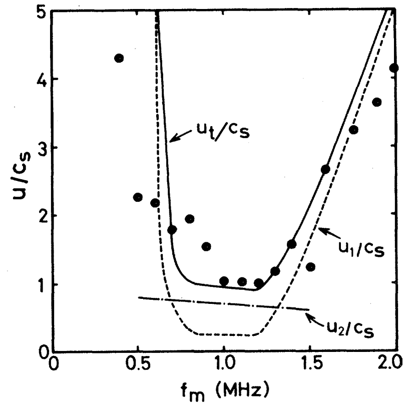

FIG. 3. Critical drift velocity of electrons u, over which parametric instability takes place, normalized by ion-acoustic speed c_s versus modulation frequency f_m with $p=3\times10^{-5}$ Torr, $V_b=200$ V, $B_0=860$ G, $\omega_l=2\pi(2\times10^5)$ sec^{-1}, $\omega_s=2\pi[(0.6-1.0)\times10^6]$ sec^{-1}, $\gamma_l=2\times10^5$ sec^{-1}, and $\gamma_s=10^5$ sec^{-1}. The results obtained experimentally (●), taken in the B-2 device, are compared with those predicted theoretically, i.e., u_1/c_s (dashed line), u_2/c_s (dash-dotted line), and $u_t(\equiv u_1+u_2)/c_s$ (full line).

old in some parameter spaces.[8] Typical experimental results are shown in Fig. 3 versus modulation frequency, where the ordinate is the ratio of the drift velocity of electrons $u=E_r/B_0$ (E_r being the radial electric field strength) to the ion-acoustic speed c_s. In the above, the value of E_r was calculated by Poisson's equation as

$$E_r=\frac{1}{\epsilon_0}\left(\frac{m}{2e}\right)^{1/2}\frac{GV_m}{2\pi r}\quad (r\geq r_b), \tag{1}$$

where m and e are the electron mass and charge, respectively. As seen in Fig. 3, the threshold becomes very low at $f_m \gtrsim f_{\text{LH}}$. In addition, the threshold drift velocity is on the same order as c_s. For the off-resonance condition, however, the threshold tends to increase rapidly.

From the phase-shift measurements, we observed for the above conditions that the f_l mode propagated almost perpendicularly to $\vec{B}_0$ with the phase velocity of the order of c_s, $v_{p\perp}{}^l \simeq 9\times10^3$ m/sec $> c_s \simeq 5\times10^3$ m/sec. The phase velocity parallel to $\vec{B}_0$ was less than the electron thermal velocity, $v_{p\parallel}{}^l \simeq 2\times10^5$ m/sec $\ll v_{Te}\simeq 1.3\times10^6$ m/sec. The momentum conservation law was satisfied by $m_s+m_l=m=0$, where $|m_{s,l}|=1$. Here, m, m_s, and m_l are the azimuthal mode numbers of the f_m, f_s, and f_l modes, respectively. Even for the case $V_m=0$, the f_l mode is present. Typically, we may write for the f_l mode $f_l/f_{ci}=2-6$. From these results, we consider the f_l mode to be the ion-acoustic wave. On the other hand, we have identified the f_s mode with the lower-hybrid wave.[8] Thus, the nonlinear interaction found above appears to be due to the lower-hybrid parametric mode conversion that is pumped by the beam.

Now we theoretically estimate the threshold, and compare it with the experimental data. According to a theory of parametric instability in a homogeneous plasma,[9] the threshold drift velocity is given by

$$\frac{u_1}{c_s}=\frac{2}{\omega_{\text{LH}}\omega_l}\left\{\frac{\gamma_l\gamma_s\omega_s}{\omega_0-\omega_s}\left[4(\omega_0-\omega_s)^2+\left(\frac{\gamma_s^2+2\gamma_l\gamma_s+\omega_l^2-(\omega_0-\omega_s)^2}{\gamma_l+\gamma_s}\right)^2\right]\right\}^{1/2}, \tag{2}$$

where ω_0 is the angular frequency of the pump field, ω_l and ω_s are those of the natural modes of the f_l and f_s modes, and γ_l and γ_s are those of the linear damping rates of these modes, respectively. Using the experimental parameters, we have calculated the threshold by Eq. (2), and plotted it as a dashed line in Fig. 3. Here, we supposed that the damping rate of the f_l mode was a result of Landau damping of both electrons and ions, while that of the f_s mode was due to Landau damping of electrons and electron-neutral collisions. As seen in Fig. 3, the threshold is resonantly reduced in the lower-hybrid resonance band of 0.6 to 1.0 MHz. In the above, the beam-produced plasma is very inhomogeneous in space, and hence the lower-hybrid frequency may change from 0.6 to 1.0 MHz corresponding to the radial density inhomogeneity; for the condition of Fig. 3, we observed $n = 7\times 10^8$ cm^{-3} at the center, and it reduced to almost half this value at $r \simeq 2$ cm. The threshold estimated above, however, is seen to be lower than that observed. As the modulation frequency is far away from the resonance band, we see that the threshold increases rapidly as a result of the frequency mismatch.

In order to elucidate the discrepancy found above, we consider the effect of density inhomogeneity (wave-number mismatch). Theoretically, this has already been done,[10] and the threshold of the resonant decay instability in the inhomogeneous plasma is written as

$$\frac{u_2}{c_s} = \frac{2\sqrt{2}\,\omega_0}{\omega_{pi}}\left(\frac{\gamma_l}{\omega_l}\right)^{1/4}\frac{1}{(kL_n)^{1/2}}, \qquad (3)$$

where L_n is the local density-gradient scale length, and k is the wave number of the decay waves. Using the experimental parameters, we obtained the numerical estimate by Eq. (3), as shown as a dash-dotted line in Fig. 3. From Fig. 3, we see that in the resonance band the threshold increases compared with that for the homogeneous plasma. In addition, the threshold gradually decreases as the modulation frequency increases. The resulting threshold may be obtained by summing Eqs. (2) and (3), and is plotted as a full line in Fig. 3. In the resonance band layer, the threshold is determined by the effect of density inhomogeneity, while the effect of frequency mismatch dominates the threshold in the off-resonance region. In the resonance band, the threshold drift velocity is on the same order as c_s. As seen in Fig. 3, the theoretical curve thus determined is in good agreement with the experimental data.

From these studies, we may conclude that rapid heating of ions as well as electrons in the modulated electron-beam–plasma system is ascribed to the lower-hybrid parametric mode conversion that is pumped by the beam. The resonant decay instability into the lower-hybrid wave and ion-acoustic wave took place in the inhomogeneous magnetoplasma.[11] Although ion quasimodes should appear to have a lower threshold than the above process,[10] we could not observe it in these experiments. The instability threshold obtained experimentally was in good agreement with that predicted by the theory only taking the effect of the density inhomogeneity into account. With extension of the studies above, it appears to be possible to achieve more energetic ion production on a large scale in a torus by modulating a relativistic electron beam near the lower-hybrid frequency.

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[11]According to Ref. 10, the resonant decay does not appear in the homogeneous plasma in the frequency range $f_m/f_{pi} \simeq 1$–3. However, if the matching condition of the wave number is satisfied in the main propagation direction (i.e., perpendicular to $\vec{B}_0$), we consider that the conservation of $k_\parallel$ is not always required, and that such a parametric decay may take place in the inhomogeneous plasma confined in a magnetic mirror.