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Improvement with High Frequency Field of Discharge Plasma by an Electron Beam

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Abstract

We study the plasma discharge process of Ar gas by an electron beam injection parallel to the magnetic field. On the lower magnetic field, waves with low frequency become strongly unstable, the discharge plasma diffuses perpendicularly to the magnetic field by unstable waves and disrupts rapidly in the short time. The unstable waves are identified as the lower hybrid wave. By the external application of high frequency (*hf*) field near the frequency of Bernstein modes, unstable waves are suppressed, so that the plasma discharge is improved. The suppression of unstable lower hybrid waves occurs, as the frequency of pump *hf* field is only lower than the frequency of the Bernstein mode. Numerical analyses due to the nonlinear theory explain reasonably the experimental ones.

Keywords:

plasma discharge, electron beam, lower hybrid waves, Bernstein modes, ponderomotive force, nonlocal nonlinear analysis

1. Introduction

The feature of the beam plasma discharge is the production of high energy electron in a magnetic mirror field whose energy is higher than the injected electron energy. A project of space experiment with particle accelerator has attempted to produce artificial aurora by injecting electron beams from a space shuttle into the ionosphere of the earth. We studied experimentally the beam plasma discharge in low gas pressure and showed that the gas break down was explained by the cyclotron damping of the plasma wave generated via the two stream instability. As the gas pressure has relatively increased, we have reported that the plasma discharge by an electron beam showed cascade-likely temporal evolution [1]. As the magnetic field is weak, we have observed that the generated plasma disrupts rapidly in the short time ($\simeq$ 100 µs). Then unstable waves with the low frequency were strongly excited. The disruption of the plasma discharge is attributed to the occurrence of unstable waves, that is, the generated plasma diffuses radially by unstable waves with the low frequency [2].

We investigate numerically and experimentally the dispersion relation of unstable waves, identify unstable modes as lower hybrid waves.

By the external application of high frequency (*hf*) field, we attempt to suppress unstable waves and to improve the plasma discharge. We analyze numerically the process of the suppression of unstable waves with low frequency, as the *hf* field is externally applied.

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2. Experimental procedures and results

Experiments were performed in a linear vacuum chamber of diameter 15 cm and 150 cm length. The argon gas pressure in the chamber was maintained at the value $5\times10^{-5}-5\times10^{-4}$ Torr. The electron gun (diameter = 1.2 cm) was set at the end of the chamber, the accelerating voltage was 500−1500 V, and the beam current was 2−20 mA. The discharge space were in a uniform magnetic field. The unstable waves were detected by the radially and axially movable coaxial probe. Plasma parameters were measured by the radially and axially movable Langmuir probe. A 450 µs electron beam pulse was injected into argon gas at 3×10^{-4}

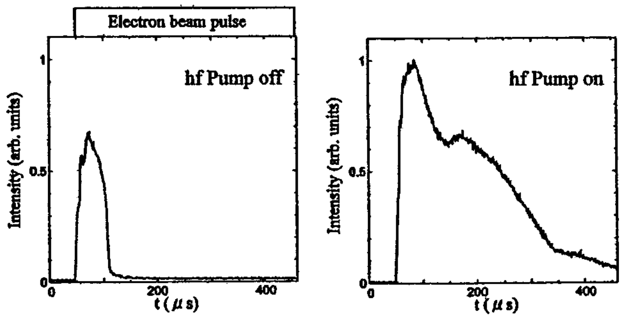

Fig. 1 Temporal evolution of light intensity detected by a photomultiplier, where $\omega_{ce}/2\pi$ = 280 MHz, beam energy V_b = 1 keV, gas pressure $p \simeq 3\times10^{-4}$. Parameters are same in Figs. 2–6.

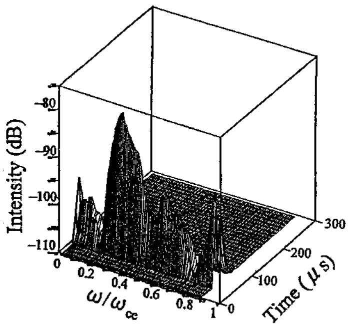

Fig. 2 Temporal evolution of frequency spectra of unstable waves with the low frequency for no *hf* field.

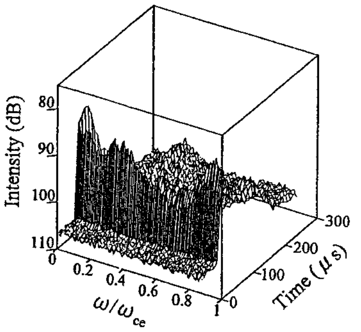

Fig. 3 Temporal evolution of frequency spectra of unstable waves with the low frequency for pump *rf* field.

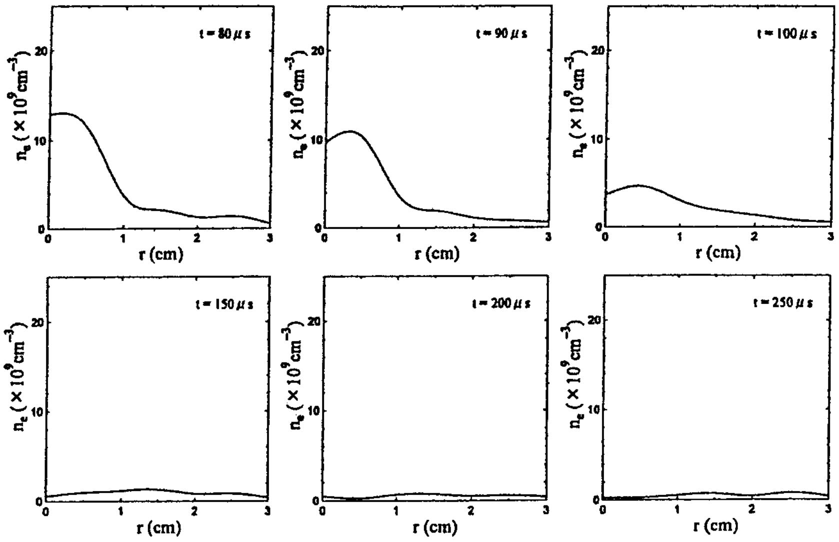

Fig. 4 Temporal evolution of the radial profile of the electron density.

Torr in the magnetic field 100 G. The visible light intensity was measured by a photomultiplier with S-4 sensitivity. The temporal evolutions of all these were investigated. The external *hf* field with the frequency 300 MHz ($\omega_0/\omega_{ce} \simeq 1.1$, where ω_0 and ω_{ce} are the frequency of *hf* field and the electron cyclotron frequency) was applied to one of accelerating electrodes of the electron beam.

Figure 1 shows temporal evolutions of the light intensity, where the time of the injection of an electron beam is 45 μs. After the rapid increment of the light, it is seen that the intensity of the light decreases in the short time ($\simeq$ 50 μs), then almost disappears.

The *hf* field near the electron cyclotron frequency is externally pumped. Then the maximum value of the light intensity ($t \simeq 90$ μs) increases by approximately one and a half times that of no *hf* pump. Although after 90 μs the light intensity decreases with time, the light does not disappear between the beam pulse (450 μs). It is seen that the plasma discharge keeps up between the beam pulse, and is much improved.

Temporal evolution of unstable waves with the low frequency are shown in Fig. 2. Waves with the low frequency $\omega/\omega_{ce} \simeq 0.32$ are strongly observed. Here, although spatial feature is not shown by figures, unstable waves is most strongly excited in the neighborhood of the center of the plasma column, unstable waves are observed in the broad range of the radial position.

Figure 3 shows temporal evolutions of unstable waves for the pump of the *hf* field. Unstable waves with frequency $\omega/\omega_{ce} \simeq 0.32$ decreases by approximately 10 dB than that of no pump of the *hf* field, also spatial reduction is seen. Figure 4 shows the temporal evolutions of radial profiles of the electron density generated by the discharge. At the early time (80 μs), the plasma via the gas break down is generated only in the injected beam region, then the maximum location of the density is the position in the center ($r = 0$ cm). When the plasma discharge begins to disrupt, the maximum location of the density move away from the center, and the radius of the plasma become larger, as seen by the radial profiles of $t = 90$ μs and $t = 100$ μs. Further as the time proceeds, the maximum location of the density moves to the large radial position in the outside. Also, with the time elapsed, the electron density n_e rapidly decreases at the first time and then gradually decreases with the time. These behaviors are similar as temporal evolutions of the light intensity. These results show that the discharge plasma diffuses radially from the center to the outside with the time elapsed. It is considered that the radial diffusion and

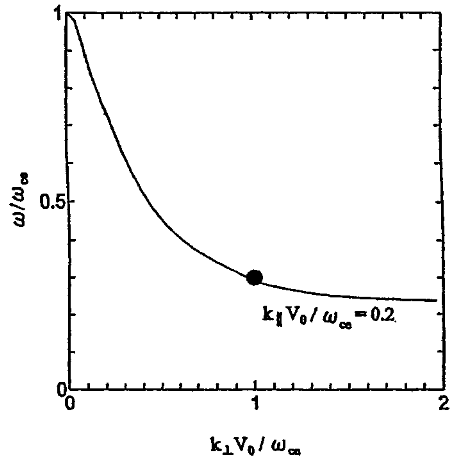

Fig. 5 Dispersion diagram of unstable waves, where electron density $n_e = 2.0 \times 10^{10}\,\mathrm{cm}^{-3}$, $T_e \simeq 5$ eV, beam density ratio n_b/n_p=0.01.

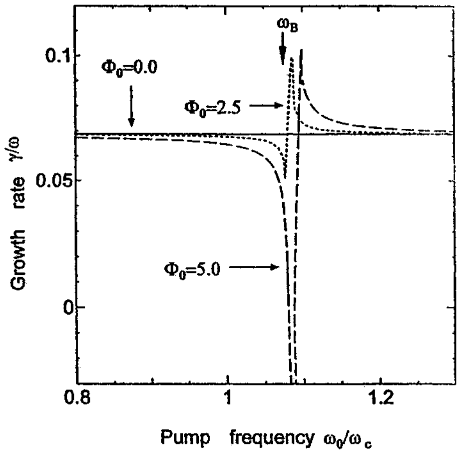

Fig. 6 Numerical growth rates versus frequency of pump *hf* field for various normalized pump field intensities, where electron density $n_e = 2.0 \times 10^{10}\,\mathrm{cm}^{-3}$, $T_e \simeq 5$ eV, beam density ratio n_b/n_p=0.01.

disruption of the plasma are attributed to the unstable waves. We attempt the identification of unstable waves. The wave number $k_{\parallel}$ parallel to the magnetic field of these waves is estimated to 0.27 cm^{-1}. Also the velocity of an electron beam v_b is 1.9×10^9 cm/s (energy 1 keV). Then observed waves (frequency $\omega \simeq 84$ MHz) satisfy $\omega = k_{\parallel} v_b$. Therefore, this unstable wave is excited by the coupling with a slow space charge wave of an electron beam. On the other hand, the wave number perpendicular to the magnetic field is estimated to 1.35 cm^{-1}. This estimation is obtained from the assumption due to that the radial profile of the wave amplitude depend on the 0th Bessel function $J(k_{\perp} r_p)$, where r_p is the plasma radius.

3. Numerical results of theory and comparisons with experiment

At the first, we calculate the dispersion relation of the lower hybrid waves by using $\varepsilon(\omega, \boldsymbol{k})$=0. Here, the dielectric function ε is given by [3]

$$\varepsilon = 1 + \chi_e + \chi_i + \chi_b, \tag{1}$$

$$\chi_e = \frac{2\omega_{pe}^2}{k^2 v_{te}^2}\left[1 + \frac{\omega}{k_{\parallel} v_{te}} \sum_{n=-\infty}^{\infty} Z\left(\frac{\omega - n\omega_{ce}}{k_{\parallel} v_{te}}\right)\exp(-\lambda_e) I_n(\lambda_e)\right],$$

$$\chi_i = \frac{2\omega_{pi}^2}{k^2 v_{ti}^2}\left[1 + \frac{\omega}{k_{\parallel} v_{ti}} Z\left(\frac{\omega - n\omega_{ci}}{k_{\parallel} v_{ti}}\right)\exp(-\lambda_i) I_n(\lambda_i)\right],$$

$$\chi_b = \frac{2\omega_b^2}{k^2 v_{tb}^2}\left[1 + \frac{\omega - k_{\parallel} v_b}{k_{\parallel} v_{tb}} \sum_{n=-\infty}^{\infty} Z\left(\frac{\omega - k_{\parallel} v_b - n\omega_{ci}}{k_{\parallel} v_{tb}}\right)\exp(-\lambda_b) I_n(\lambda_b)\right],$$

$$\lambda_\alpha = \frac{k_{\perp}^2 v_{t\alpha}^2}{2\omega_{c\alpha}}, \quad (\alpha = e, i, b),$$

where ω_{pe}, ω_{pi} and ω_{pb} are plasma frequencies of the electron, ion and electron beam, respectively, $\omega_{ce} (= \omega_{cb}), \omega_{ci}$ are electron and ion cyclotron frequencies, respectively, v_{te}, v_{ti} and v_{tb} are thermal spreads of the electron, ion and electron beam, respectively, v_b is a drift velocity of the electron beam, I_n is nth modified Bessel function, Z is the plasma dispersion function and other notations are standard.

The numerical dispersion relation $\omega - k_{\perp}$ diagram is shown by the solid curve in Fig. 5, and the experimental one is plotted by the circle. The experimental plot satisfies the dispersion relation of the lower hybrid wave. Therefore, This unstable wave is identified as lower hybrid waves.

The *hf* field with the frequency ω_0 near the electron cyclotron frequency of the electron cyclotron harmonic modes (Bernstein mode) is externally applied. Then lower and upper sideband waves (frequency ω_1 and ω_2) appear around the frequency ω_0 by the coupling between unstable lower hybrid waves with the frequency ω, the relation $\omega_{1,2} = \omega_0 \pm \omega$ satisfies, and amplitudes of both sideband waves have nearly equal magnitude. These sideband fields interact with the pump *hf* field and a ponderomotive force acting on the low frequency unstable waves is generated.

It is considered that this ponderomotive force suppresses unstable waves [4]. We attempt the numerical analysis of unstable waves in the presence of the applied *hf* field. The analysis is performed by taking the boundary condition perpendicular to the magnetic field as the cylindrical beam and plasma column *i.e.*, the nonlocal theory. The treatment is similar to that in ref. [4], and the ponderomotive force due to the pump *hf* field and fields of both sideband waves is taken in nonlinear terms. The obtained nonlinear dispersion relation is given by

$$\varepsilon + \frac{\mu_1}{\dfrac{\omega_T k_{1\parallel} r_0}{\omega_0 - \omega} - \lambda_{n_1, \ell_1}} + \frac{\mu_2}{\dfrac{\omega_T k_{1\parallel} r_0}{\omega_0 + \omega} - \lambda_{n_2, \ell_2}} = 0, \tag{2}$$

$$\mu_{1,2} = \frac{\omega_{pi}^4}{\omega_{ci}^2 \omega_0^2} \Gamma_n^2 \Gamma_{n_1, n_2}^2 \ell_{1,2}^2 \left| \int_0^{r_0} \left(1 - \frac{r^2}{r_0^2}\right) \frac{r}{r_0} \right.$$

$$\left. \times J_{\ell}(k_{\perp n} r) \frac{\partial \Phi_0^{2}}{\partial r} e^{-\frac{\xi_{1,2}}{2}} \xi_{1,2}^{\ell_{1,2}} L_{n_{1,2}}^{\ell_{1,2}}(\xi_{1,2}^2)\, dr \right|^2,$$

$$\Phi_0 = \frac{(e/m_e)\,\phi_0}{c_s^2},$$

$$\xi_{1,2}^2 = \frac{\omega_B k_{1,2\parallel} r_0}{\omega_{1,2}} \frac{r^2}{r_0^2}, \quad \lambda_{n_{1,2}, \ell_{1,2}} = 2(2n_{1,2} + \ell_{1,2} + 1).$$

where ε is the local linear dielectric function shown by eq. (1), (ω ,k), (ω_0, k_0), (ω_1, k_1) and (ω_2, k_2) are the unstable, pump *hf*, lower and upper sideband modes, ϕ_0 is the wave potential of *hf* field, c_s is ion acoustic velocity, Γ_n and $\Gamma_{n_{1,2}}$ are the normalized factor. With respect to the wave potential for the finite mode of each wave, $n_{1,2}$ and $\ell_{1,2}$ are radial and azimuthal mode numbers of each mode, r_0 is the plasma radius, J_ℓ is ℓth Bessel function, L_n^ℓ is nth and $\ell-$order generalized Laguerre polynomials, and other notations are standard. Also ω_B is the frequency of Bernstein modes as the normal modes in plasma. We have calculated the growth rates of unstable lower hybrid waves for the pump *hf* field from eq. (2). The growth rates of unstable waves as a function of the frequency of the pump *hf* field are shown in Fig. 6 for various applied normalized potential Φ_0 of the *hf* field. It is seen that growth rates of unstable waves are reduced, when the frequency ω_0 of pump waves is less than the frequency ω_B of the Bernstein mode, the growth rate of waves is decreases with increasing of the intensity of the pump wave, and then waves damps for $\Phi_0 = 5.0$. Also, when ω_0 is higher than ω_B, growth rates of unstable waves increase. Therefore, although the pump of *hf* field enables to suppress the unstable lower hybrid waves, the suppression is very sensitive to the pump frequency.

Bernstein modes with $\omega_B/\omega_{ce} \simeq 1.08$ can exist experimentally under the present plasma condition. These numerical behaviors explain reasonably the suppression of unstable lower hybrid waves in the experiment on the pump *hf* field.

4. Conclusions

On the condition of the lower magnetic field in the plasma discharge process of neutral gases by an electron beam, the plasma disrupts rapidly in the short time. Then the low frequency waves are strongly excited. These unstable waves are diffused the plasma perpendicularly to the magnetic field, and introduce to the disruption of the plasma discharge. The unstable waves are identified as the lower hybrid waves by comparing the dispersion relation. The pump of the *hf* field enables to suppress unstable lower hybrid waves, the plasma discharge is well improved. The suppression of unstable waves is due to the ponderomotive force of the pump *hf* field and fields of both sideband waves. This suppression occurs, as the frequency of the pump *hf* is only lower than the frequency of Bernstein modes. Numerical analyses are carried out by the nonlinear theory. Numerical results explain reasonably the experimental ones.

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