$=v_{e\,\mathrm{th}}(m_e/m_i)^{1/2}$. Because $\partial\omega/\partial k = 3k_0 v_{e\,\mathrm{th}}^2/\omega_p$, the maximum value of k_0 after the condensation is given by $(\omega_p/v_{e\,\mathrm{th}})(m_e/m_i)^{1/2}/3$. For the present mechanism to be possible this value should be smaller than ω_p/c. This condition gives $T_e > 50$ eV for an electron-proton plasma, but the critical electron temperature is reduced in proportion to the ion mass. When $k_0 > \omega_p/c$, the excitation of the left-hand–polarized electromagnetic wave is still possible by the nonlinear cyclotron damping of electrons (these considerations will be published elsewhere).

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Excitation of Pure Electron Plasma Waves by Modulated Electron Beams

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A new type of exciter consisting of electron beams for launching electron plasma waves is investigated experimentally and theoretically. When fast electron sheet beams, modulated at a prescribed frequency, are injected into plasmas, electron plasma waves are found to be excited nearly perpendicularly to the electron beams. Compared with a mesh excitation, we found that the beam excitation has several merits: it hardly excites ballistic modes, the direct coupling due to an electrostatic induction with another probe is small, and it can even be used in a very hot plasma.

There have been reported several types of exciters of electron plasma waves, i.e., a wire probe,[1] a gridded parallel coupler,[2] and parallel plate grids.[3] All of these are metal-type exciters, which easily excite the ballistic mode[4,5] via the sheath around the metal. In this Letter, we report on the excitation of electron plasma waves by electron sheet beams as an electron version of an excitation of ion waves by ion beams.[6]

Experiments were performed in two types of vacuum chambers. One is 160 cm in length and 32 cm in diameter at Tohoku University. Argon gas is used at a pressure $P = (4-6)\times10^{-4}$ Torr. Forward-diffusion-type plasmas are used for the experiments. The typical parameters are $N_0 = (1-2)\times10^7$ cm^{-3} (density) and $T_e = 3-6$ eV (electron temperature). Another is 120 cm in length and 60 cm in diameter at the Institute of Space and Aeronautical Science, University of Tokyo. Plasma sources of a back diffusion type are used for the experiments. The typical plasma parameters are $N_0 = (0.5-2)\times10^7$ cm^{-3} and $T_e = 3-4$ eV. The electron sheet beams are injected into the plasmas through a slit 5 cm in length and 0.5 cm in width. The electrons are produced by a hot cathode. For the wave excitation, the electron sheet beams, modulated at a prescribed frequency, are injected into plasmas across the chamber.

In Fig. 1(a), we show the electric circuit for the excitation and the detection of electron plasma waves. In Fig. 1(b), the spatial distribution of the electron current across the beam is shown with the beam velocity as a parameter. The effect of the existence of the electron beam is clearly shown for the various beam velocities. The excited waves are detected by a circular planar mesh shielded by meshes. The typical wave patterns excited by electron sheet beams are indicated in Fig. 1(c) as the modulation frequency of the beams is varied.

The dispersion relation and damping coefficients obtained by electron-sheet-beam excitation are shown in Fig. 2, in which the experimental results obtained by a mesh excitation are also plotted. The experimental results obtained by the beam excitation are nearly in accord with those obtained by mesh excitation. It must be noted that the free-streaming mode, easily excited by mesh excitation, is hardly excited by the beam excitation. When the modulation voltage of the electron beams is changed, the amplitude of the excited waves is found to be nearly proportional to the modulation voltage which is less than 1 V peak to peak.

In Fig. 3(b), the effect of a direct coupling due to an electrostatic induction is shown for both beam and mesh excitation by changing the phase

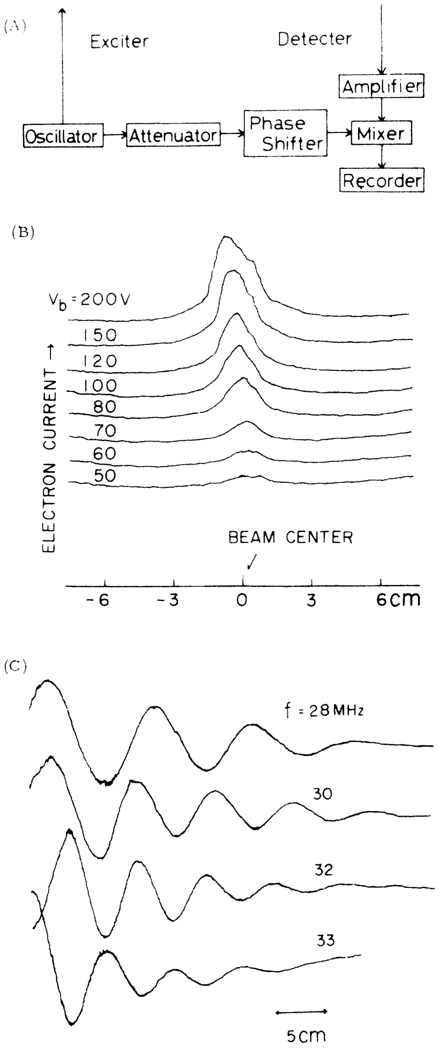

FIG. 1. (a) Electric circuit for the excitation and the detection of the electron waves. (b) The typical electron current across the electron sheet beams measured with a cylindrical probe, which is 10 cm distant from the slit. The zero level is for V_b=50 V. The level for a larger voltage is shifted successively. V_b indicates the electron beam velocity in electron volts. (c) The typical wave patterns of the electron plasma waves propagating perpendicularly to the electron sheet beams. f_{pe}=23 MHz, V_{ex}=0.4 V peak to peak.

shifter shown in Fig. 1(a). The phase shifter can control the phase of the reference signal. A large change of the wave patterns due to the change of the reference phase is directly associated with the direct capacitive coupling. In the beam excitation, the electrostatic direct coupling is found to be much smaller than that in the mesh excitation.

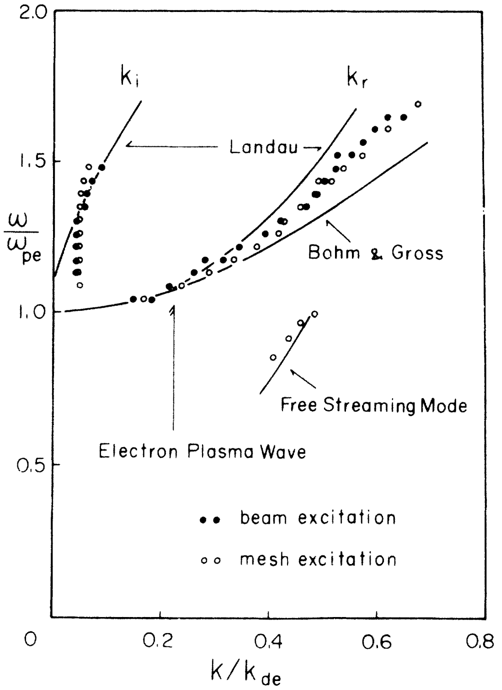

FIG. 2. Dispersion curves obtained by beam and mesh excitation. The damping factor is also plotted. Solid curves, theoretical results.

We now investigate theoretically the mechanism of the wave excitation by electron sheet beams. The coordinate system for the sheet beam is chosen as in Fig. 3(a). From the fundamental equations for electron plasma waves, i.e., the continuity equation, the momentum equation, and Poisson's equation, one can obtain the following wave equations for the electron plasma waves by assuming the temporal term as proportional to $e^{i\omega t}$:

$$\Delta^2 n + k^2 n = -\rho(\vec{r}), \tag{1}$$

$$k^2 \equiv (\omega^2 - \omega_{pe}^2)/\gamma C_e^2 \tag{2}$$

$$\rho(\vec{r}) \equiv (-\omega_{pe}^2 n_b + i\omega S_b)/\gamma C_e^2, \tag{3}$$

where n, k, ω, ω_{pe}, and $\sqrt{\gamma} C_e$ denote the electron density, the wave number, the angular frequency, the electron plasma frequency, and the electron thermal velocity, respectively. The effect of the electron sheet beam is included in the source term (S_b) in the continuity equation and in the charge density of the electron beam in Poisson's equation (n_b). The source term S_b is produced by an ionization, etc., by the electron beam. The solution of Eq. (1) for a sheet source with an infinite length can be obtained in the form

$$n(\vec{\mathrm{r}}) = -\tfrac{1}{4}i\int_{-a}^{a}dx'\int_{-b}^{b}dz'\,\rho(r')H_0^{(2)}((k^2-k'^2)^{1/2}r'), \tag{4}$$

where $H_0^{(2)}((k^2-k'^2)^{1/2}r')$ is a Hankel function of the second kind, r' is the distance from the observation point to the source point in the x-z plane, and $\vec{\mathrm{r}}$ denotes the coordinate of the observation point. In Eq. (4), the wave number k' is introduced for a phase variation of the sheet beams in the y direction due to a transit-time effect. The value of k' can be expressed as $k' = \omega/V_0$ (V_0 being the beam velocity) for our experiments. From Eq. (4), one can obtain the following relation for a far-field approximation ($R \gg a, b$):

$$n(R,\theta) = \frac{(1-i)\rho e^{-iKR}}{(\pi KR)^{1/2}}\,\frac{\sin(Ka\sin\theta)}{K\sin\theta}\,\frac{\sin(Kb\cos\theta)}{K\cos\theta}, \tag{5}$$

where R is the distance from the origin (the center of the beam cross section) to the observation point, and $K \equiv (k^2-k'^2)^{1/2}$. The angle θ is between the z axis and the radial line from the origin to the observation point. For the experimental conditions of $\theta = 0$, Eq. (5) reduces to

$$n(z) = \frac{(1-i)a(-\omega_{pe}^2 n_b + i\omega S_b)}{\gamma C_e^2}\,\frac{\sin[(k^2-k'^2)^{1/2}b]}{(k^2-k'^2)^{3/4}}\,\frac{\exp[-i(k^2-k'^2)^{1/2}z]}{(\pi z)^{1/2}}. \tag{6}$$

The value of n is found to be proportional to n_b and S_b. Equation (6) also shows that the electron plasma wave is excited nearly perpendicularly to the sheet beam for the present case of $k^2 \gg k'^2$; $k' = \omega/V_0 \approx 0.05$ cm^{-1} for $V_b = 100$ V and $f = 30$ MHz, and $k \approx 0.7$ cm^{-1} for $f = 30$ MHz.

We now discuss the experimental results of Fig. 2. The dispersion relation of electron plasma waves is expressed as

$$k_{\mathrm{D}e}Z'(\omega/\sqrt{2}kC_e)/2k^2 = 1, \tag{7}$$

where Z' is the derivative of the plasma dispersion function and $k_{\mathrm{D}e} = \omega_{pe}/C_e$. From Eq. (1), one can obtain the well-known Bohm-Gross relation, $\omega^2 = \omega_{pe}^2 + 3k^2C_e^2$, which corresponds to the relation obtained from Eq. (7) with an assumption of weak damping. Although both relations are plotted in Fig. 2, the Bohm-Gross relation is, for simplicity, used for deriving the exciting mechanism in Eqs. (1)-(3). Figure 2 shows that the dispersion curves of the experimental results are nearly in accord with the theoretical curves. The theoretical damping factor k_i, which is due to Landau damping, is roughly in accord with the experimental results for frequencies larger than $\omega/\omega_{pe} = 1.3$. For lower frequencies, however, the observed damping is appreciably greater than Landau damping. The difference is considered to be mainly due to electron-neutral collisions. It is noted here that the damping due to the factor of $(kz)^{-1/2}$ in Eq. (6) is much less than the observed damping in our present experimental conditions.

For the frequency lower than the plasma frequency, the observed signals for the mesh excitation can be explained as the free-streaming mode,

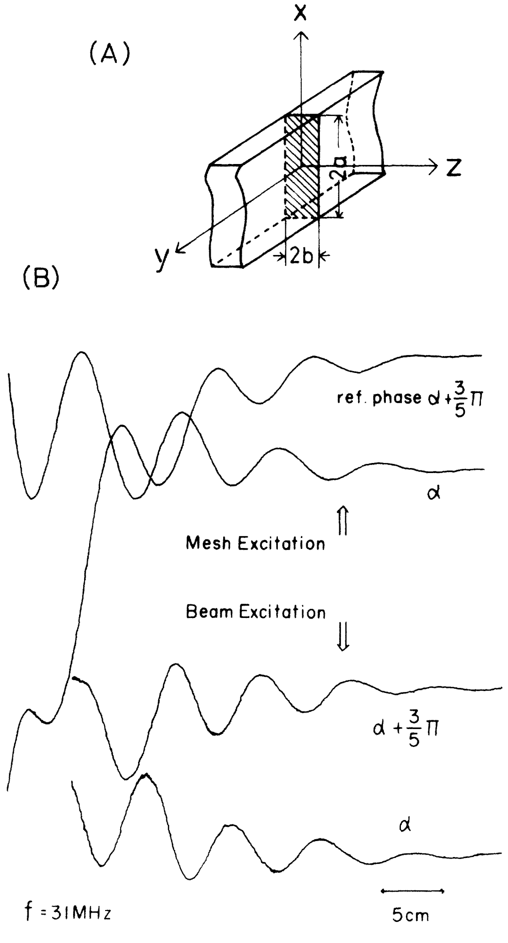

FIG. 3. (a) The coordinate system for sheet beams. (b) Effect of the phase of reference signals in Fig. 1(a). The start positions for beam and mesh excitation are 10 and 5 cm from the exciter, respectively. The experimental conditions of the plasma frequency for both excitations are slightly different.

i.e., the pseudowave described by the relation $\omega/k \propto C_e^{2/3}(\omega z)^{1/3}$.[4,5] The dispersion curve in the figure is plotted at a fixed value of z. The corresponding experimental plots are qualitatively in accord with this free-streaming mode, which was easily excited by the mesh excitation, but could not be observed in the beam excitation.

Figure 3(b) shows that the direct coupling due to electrostatic induction is small for the beam excitation, in contrast with the large observed coupling for the mesh excitation. The small direct coupling for the beam excitation may be useful in many experiments.

The experimental result that the wave amplitude changes linearly with the modulation voltage of the beams is in accord with the theoretical results of Eq. (6), because n_b and S_b are considered to be proportional to the modulation voltage. Furthermore, the beam-excited waves which propagate nearly perpendicular to the beams can be also explained by the theoretical results of Eq. (6).

In conclusion, by injecting fast electron sheet beams into plasmas, the electron plasma wave is found to be excited nearly perpendicularly to the sheet beams. The amplitude and frequency of excited waves can be controlled by varying the modulation voltage and frequency of the beams. By comparing the beam-excited waves with the conventional mesh-excited waves, the beam excitation is found to excite the pure electron-plasma mode. That is, the free-streaming mode which is easily excited for the mesh excitation cannot be observed for the beam excitation. Furthermore, the direct coupling due to the electrostatic induction is found to be small for the beam excitation.

The beam excitation can be concluded to be a very useful means for the excitation of pure electron plasma waves.

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CO_2-Laser—Beam Absorption by a Dense Plasma

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We study the absorption of a CO_2-laser beam by an independently produced plasma at approximately the critical density. The measured fractional absorption coefficient agrees with that associated with inverse bremsstrahlung for incident laser intensities below 10^{10} W/cm^2. Above this value, an abrupt increase in absorption is observed.

Plasma production and heating by high-power lasers has been the subject of numerous theoretical and experimental studies for several years. Recently, however, this field of research has acquired a new dimension as a result of the proposal for using laser-imploded DT pellets to demonstrate the feasibility of controlled thermonuclear fusion.[1] One of the main problems to be solved in this context is the coupling of laser energy to the plasma. Indeed, at high incident intensities the temperatures obtained are too high for classical collisional absorption (i.e., inverse bremsstrahlung) to be efficient. Anomalous collisionless mechanisms must then take over the absorption. These mechanisms, generally involving parametric instabilities, have been the subject of several theoretical papers.[2] However, no direct evidence of anomalous absorption in laser-produced—plasma experiments has been reported up to now.[3] One of the possible rea-