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Excitation of Low-Frequency Oscillation by Electron Beam in a Special Plasma Device

Teiichiro YAGI, Shigenobu KUMAZAWA, Tsuneyasu KURA and Yoshimi FUJITA

Department of Physics, Faculty of Science, Kanazawa University, Kanazawa 920

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Abstract By means of injecting the electron beam into the plasma of plasma source with a built-in grid near the cathode, connected to a diffusion sphere, the excitation of the fundamental and higher harmonics of low-frequency oscillation, which seems to be ion oscillation, has been observed. Furthermore, the existence of the threshold value in the electron-beam current for this excitation has been found. Possible mechanism of the excitation is discussed.

1. Introduction

Several experiments have been carried out about the excitation of ion oscillation by electron beam. As concerns the case of no-magnetic field, Linder and Hernqvist[1] and Hernqvist[2] observed the ion oscillation excited in the electron beam. Kawabe et al.[3] observed the excitation of ion oscillation by means of injecting the electron beam into the back-diffusion type plasma device. Tanaka[4] observed the temporally damping oscillation in the electron beam with the frequency approximately equal to ion oscllation. Under the magnetic field, Hernqvist[5] observed the excitation of ion oscillation in the electron beam. Vermeer et al.[6] observed the instability of oscillation with the lower hybrid frequency under the condition of finite boundary, which was approximately equal to the frequency of ion oscillation under their experimental condition. Yatsui et al.[7] found the low-frequency oscillation in the beam-plasma discharge of finite boundary, which is due to the coupling of ion plasma waves of plasma and slow cyclotron wave of beam. Mechanism of the excitation in the cace of no-magnetic field is not so obvious, compared to the case under the magnetic field.

Recently we reported that the higher harmonics of ion oscillation were excited quite steadily in the plasma device PDI[8] consisting of the plasma source with a built-in grid near the cathode and the diffusion sphere connected to it. This time, we have constructed a new plasma device PD2 which is similar to PD1 except that the electron gun is attached. Using this apparatus, we have observed the low-frequency oscillation caused by the electron beam which seems to be ion oscillation. Preliminary report on it will be presented here.

2. Experimental Apparatus

Plasma device PD2 is illustrated in Fig.1. Like PD1, the plasma source (the part from A to C) of direct-current discharge with a built-in grid grounded near the cathode is attached to a diffusion sphere. The cathode consists of six tungsten filamets connecting in parallel. The grid is a mesh of intervals of 2.5mm in length and width, consisting of tungsten wire of 0.2mm ϕ. The probe consists of tungsten wire of 0.1mm ϕ and 5mm in length and is movable by means of a bellows and a micrometer screw. The electron gun is installed in the diffusion sphere, which is so-called Pierce type possessing four focusing plates with the hole of 5mm ϕ. Beam current is measured by the Faraday cup behind the anode. Signal is pulled out from the movable receiver, which is the same mesh as the grid and grounded through 10KΩ resistance, and frequency-analyzed by means of the field intensity meter of superheterodyne type. Mercury vapor at about 2×10^{-4} Torr. is used.

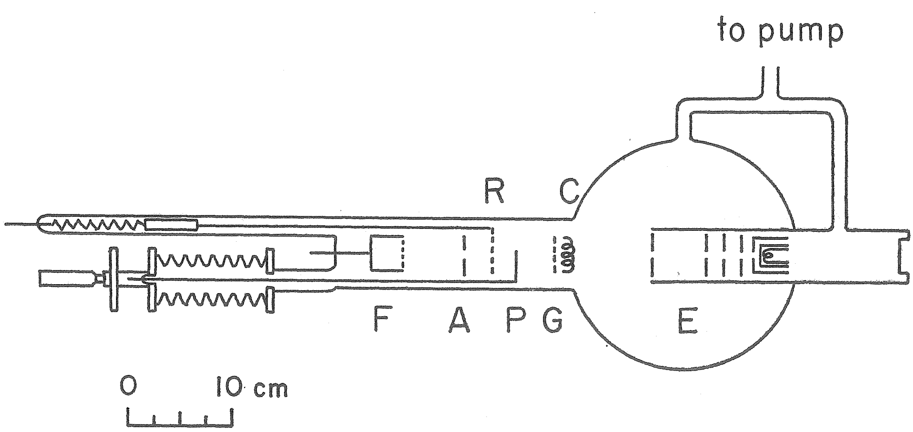

Fig. 1. Plamsa Device PD2. F : Faraday cup A : anode R : movable receiver P : movable probe G : grid C : cathode E : electron gun

3. Experimental Results

In PD2 like PD1 too, it is found that the higher harmonics of ion oscillation are spontaneously generated in a usual condition without electron beam. However, when the heater current of plasma source is decreased, spontaneous ion oscillations attenuate extremely or vanish completely in a certain range of anode current. If electron beam is injected into the plasma source in such a state, then the harmonics of low-frequency oscillation are excited. Its behavior is illustrated in Fig. 2, which shows the fundamental oscillations only. Table Ia and Ib are the results of probe measure-

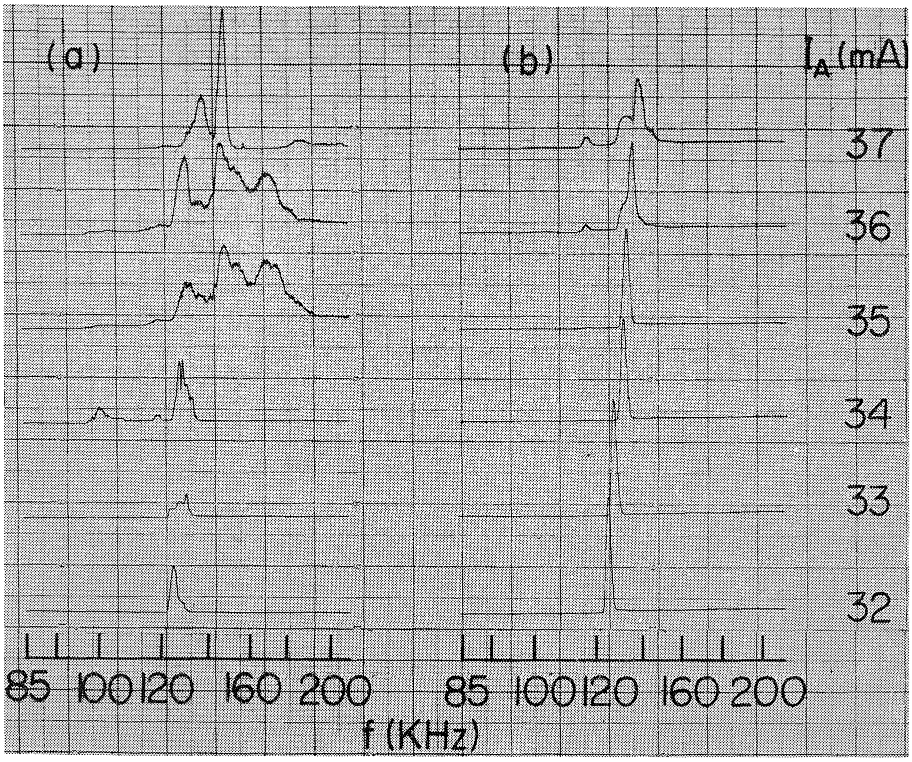

Fig. 2. Frequency spectra.
(a) no beam (b) beam injected; I_A is discharge current.
Acceleration voltage is 250V and beam current 250 μ A.

Table Ia. Results of probe measurements in the case of Fig. 2 (a) (no beam).
I_A : discharge current T_e : electron temperature
V_p : plasma potential n_e : electron density
f_{pi} : calculated frequency of ion oscillation
λ_D : Debye length

I_A(mA)	T_e(eV)	V_p(V)	n_e($\times 10^7 cm^{-3}$)	f_{pi}(KHz)	λ_D(mm)
32	0.98	2.1	7.21	125.7	0.87
33	0.79	2.0	8.06	133.0	0.74
34	0.93	2.2	7.68	129.6	0.81
35	1.17	2.9	8.38	135.5	0.88
36	1.19	2.9	8.22	134.2	0.90
37	1.24	3.0	8.75	138.3	0.89

Table Ib. Results of probe mesurements in the case of Fig. 2 (b) (beam injected). Notations are the same as Table Ia.

I_A(mA)	T_e(eV)	V_p(V)	n_e($\times 10^7$cm^{-3})	f_{pi}(KHz)	λ_D(mm)
32	1.50	3.3	7.55	128.5	1.05
33	1.46	3.4	8.79	138.4	0.96
34	1.53	3.0	7.92	131.8	1.03
35	1.52	3.3	7.90	130.7	1.03
36	1.51	3.6	8.71	138.0	0.98
37	1.51	3.4	8.62	137.3	0.98

ments corresponding to Fig.2(a) and2(b) respectively, besides the calculated frequencies of ion oscillation and the calculated Debye lengths with those data. Probe measurements are carried out at the position of 8mm in front of the receiver at the middle between the grid and the anode. Comparing Table Ia and Ib, it is seen that the electron temperatures and the plasma potentials of Ib are higher than those of Ia, but the electron densities are not too much different each other. This fact suggests that the excitation of low-frequency oscillation is not related to the change of the global state of plasma owing to the electron beam, but is caused by some beam-plasma interaction as discussed later.

The frequency f_{pi} of ion oscillation is calculated with the use of Tonks-Langmuir's formula[9]

$$f_{pi}=\left(\frac{n_e\ e^2}{\pi\ M_i}\right)^{\frac{1}{2}}, \qquad (1)$$

where n_e is the electron density, e is the electron charge and M_i is the ion mass. Fig.3 shows the observed frequencies including the harmonics and the calculated f_{pi} tabulated in Table Ib and their multiples. The agreement between two quantities is very good. Therefore, the observed low-frequency oscillation seems to be ion oscillation. Fig.4 shows the relative intensities of the harmonics of the observed low-frequency oscillation.

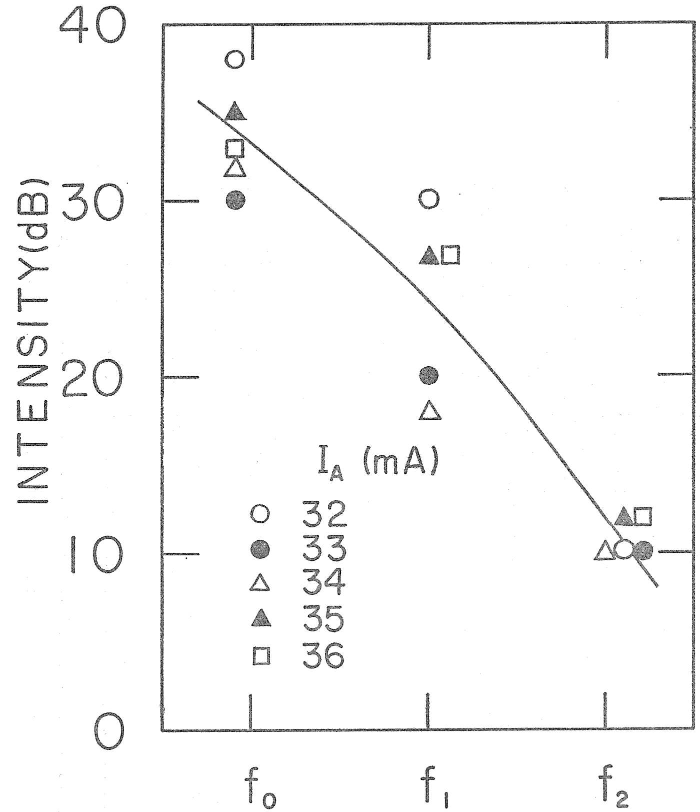

Fig. 4. Intensities of the harmonics of the oscillation in the case of Fig. 3. ObB is 1μV.

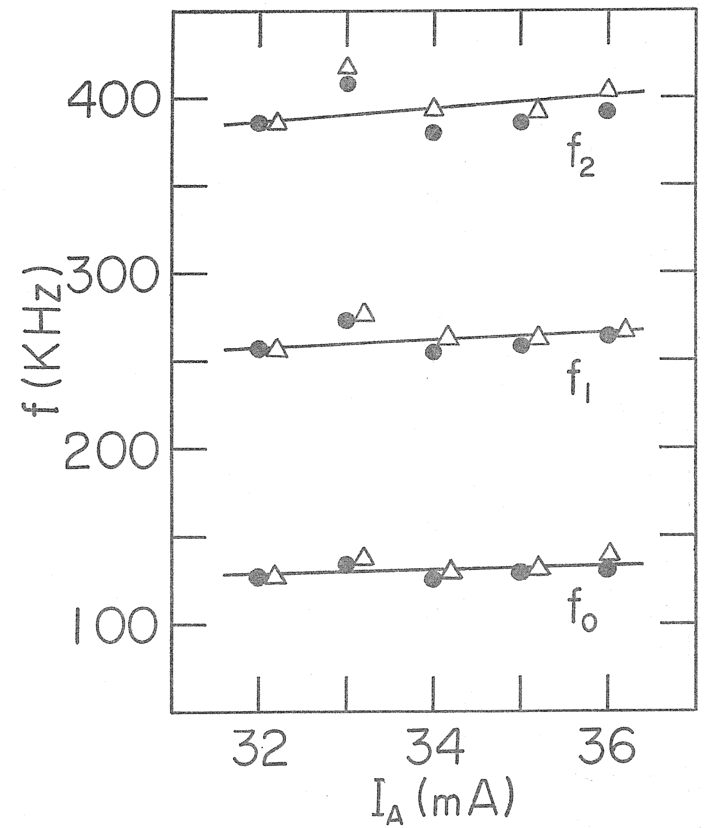

Fig. 3. Comparison of the observed frequencies with the calculated frequencies of ion oscillation.
Solid circle : observed frequency open triangle : calculated frequency of ion oscillation f_0 : fundamental f_1 : 1st harmonic f_2 : 2nd harmonic Acceleration voltage is 250V and beam current 250μA.

When the beam current is changed, keeping the anode current constant, the similar behavior is observed, as illustrated in Fig. 5. As seen from the lower curves in Fig. 5, the spectrum is noisy when the beam current is small. At 50 μA of the beam current, the noises reach maximum, and besides the slight excitation of ion oscillation can be observed. At the beam current equal to or larger than 100 μA, remarkable excitation of ion oscillation can be seen in the rather quiescent spectrum. From this result, the threshold value of the beam current for the excitation of ion oscillation is estimated as 50μA, corresponding to the beam density of about 1.7×10^6 cm^{-3}. Table II shows the results of probe measurements in this case. The electron temperature and

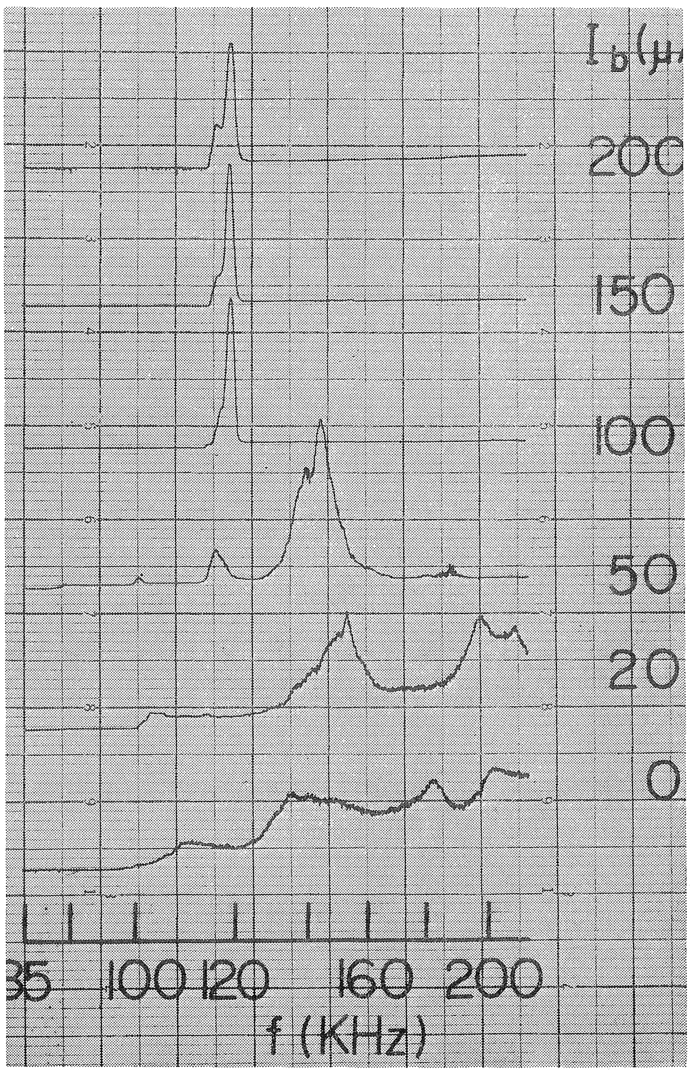

Fig. 5. Frequency spectra when beam current I_b is changed. Discharge current is 32mA and acceleration voltage is 250V.

the plasma potential are not influenced by the electron beam, but the electron density decreases slightly as the beam current increases, on the contrary to the case of Table I. This seems to be due to the effect of the noise upon the probe measurements.

Table II. Results of probe measurements in the case of Fig. 5. I_b is the beam current. Other notations are the same as Table Ia.

$I_b(\mu A)$	T_e(eV)	V_p(V)	$n_e(\times 10^7 cm^{-3})$	f_{pi}(KHz)	λ_D(mm)
0	1.01	2.4	8.40	136.7	0.81
20	1.00	2.4	8.30	132.7	0.83
50	1.16	2.7	7.56	128.7	0.92
100	1.05	2.2	7.42	127.4	0.88
150	1.07	2.3	7.54	128.5	0.88
200	1.00	2.2	7.55	128.5	0.86

4. Discussions

Using the special plasma device PD2, the excitation of low-frequency oscillation by the electon beam, which seems to be ion oscillation, was observed. According to Briggs,[10] the mutual interaction between a hot-electron plasma and a electron beam in the case of no-mognetic field and no boundary leads to the instability of ion oscillation with infinite growth rate, when $\eta=(n_b/n_p)\ (T_e/2V_o)>1$. Here, n_e is the density of electron beam, n_p is the electron density of plasma, T_e is the electron temperature of plasma (eV) and V_o is the energy of electron beam (eV). In the case of I_A=32mA～36mA in Table Ib, $\eta=2.8\sim3.4\times10^{-4}$. Accordingly Briggs' theory may not be applicable.

As another excitation mechanism, we consider the so-called potential-minimum oscillation of ions trapped in the trough of potential formed between the cathode and the grid, which are both grounded in PD2. Zollweg and Gottlieb[11] have given the theory on this model, according to which the frequency is given by

$$f^2=\frac{f^2_{pi}}{1+(\lambda/\lambda_D)^2}, \qquad (2)$$

where $\lambda=4d$, $2d$ being the width of the trough and λ_D is the Debye length, f_{pi} is the frequency of ion oscillation corresponding to the mean ion density $\bar{n}_i$ in the trough. If we assume $\bar{n}_i=\bar{n}_e=n$ as the upper limit of $\bar{n}_i$, eq. (2) is reduced to

$$f^2 = \frac{\dfrac{e^2}{\pi M_i}}{\dfrac{1}{n} + \dfrac{4\pi e^2}{kT}(4d)^2} \quad . \qquad (3)$$

Substituting the numerical values of e, M_i, k (Boltzmann's constant) and $2d=1$cm (cathode-grid distance) and $T=1500°$K assumed, we have

$$f^2 = \frac{2.19 \times 10^2}{\dfrac{1}{n} + 5.56 \times 10^{-5}} \quad , \qquad (4)$$

from which $f<1.98$ KHz. This value of f is less than one sixty-fifth of the observed frequencies. Thus this model fails to account for our oscillation.

Finally, we consider the Pierce's mechanism.[12] In our case, the spacing of the grid is only a little iarger than the Debye length λ_D as written in Table Ib. Therefore the mesh is perfectly covered by the ion sheath. Furthermore, the plasma potential is about two times of the electron thermal energy, so the plasma electrons are unable to go across the grid while the plasma ions drift towards the cathode across it. Thus, it may be possible that there exists an ion cloud between the grid and the cathode. According to Pierce, the mutual interaction between this ion cloud and electron beam leads to the excitation of low-frequency oscillation. If there exists the ion cloud actually, this model may account for our experiment, e. g. the frequencies and the threshold value of electron beam for the excitation etc..

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