

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

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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<sup>1)</sup> and Hernqvist<sup>2)</sup> observed the ion oscillation excited in the electron beam. Kawabe et al.<sup>3)</sup> observed the excitation of ion oscillation by means of injecting the electron beam into the back-diffusion type plasma device. Tanaka<sup>4)</sup> observed the temporally damping oscillation in the electron beam with the frequency approximately equal to ion oscillation. Under the magnetic field, Hernqvist<sup>5)</sup> observed the excitation of ion oscillation in the electron beam. Vermeer et al.<sup>6)</sup> 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.<sup>7)</sup> 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 case 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<sup>8)</sup> 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 filaments connecting in parallel. The grid is a mesh of intervals of 2.5mm in length and width, consisting of tungsten wire of 0.2mm  $\phi$ . The probe consists of tungsten wire of 0.1mm  $\phi$  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  $\phi$ . 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  $10K\Omega$  resistance, and frequency-analyzed by means of the field intensity meter of superheterodyne type. Mercury vapor at about  $2 \times 10^{-4}$  Torr. is used.

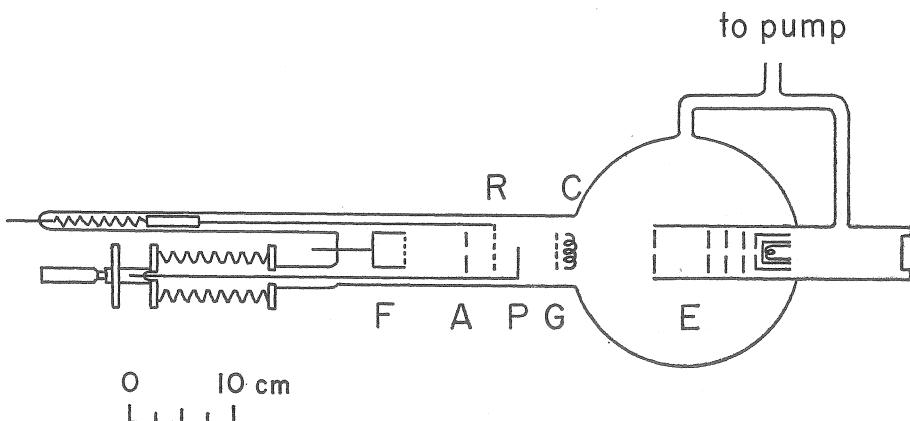


Fig. 1. Plasma Device PD2. F : Faraday cup A : anode R : movable receiver  
P : movable probe G : grid C : cathode E : electron gun

## 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-

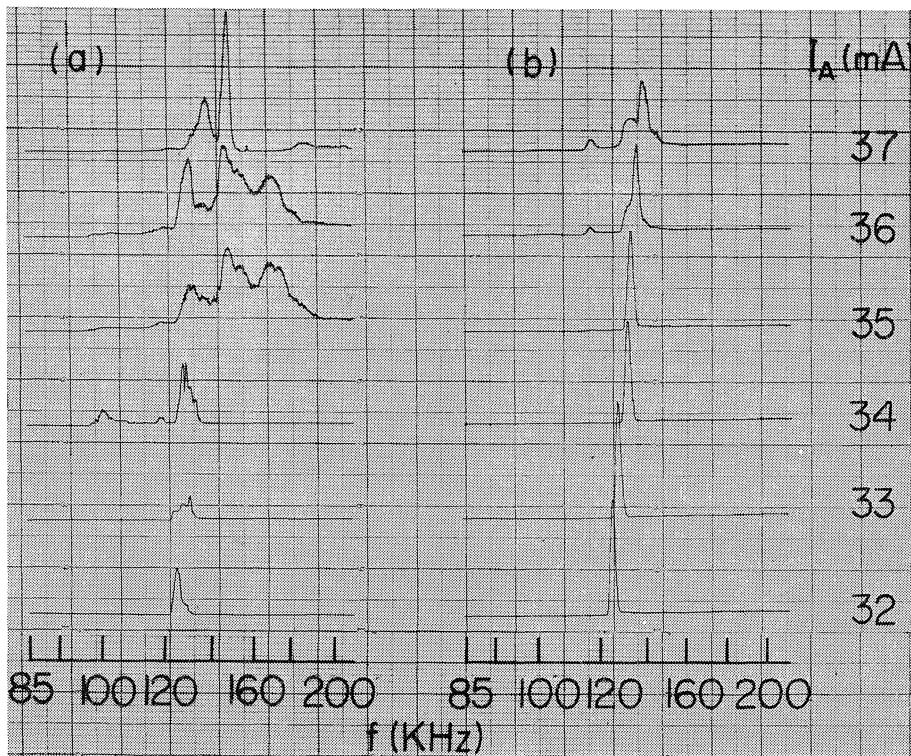


Fig. 2. Frequency spectra.

(a) no beam (b) beam injected;  $I_A$  is discharge current.Acceleration voltage is 250V and beam current  $250 \mu A$ .

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 $\lambda_D$  : Debye length

| $I_A$ (mA) | $T_e$ (eV) | $V_p$ (V) | $n_e (\times 10^7 \text{cm}^{-3})$ | $f_{pi}$ (KHz) | $\lambda_D$ (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 measurements 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) | $n_e (\times 10^7 \text{cm}^{-3})$ | $f_{pi}$ (KHz) | $\lambda_D$ (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) and 2(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<sup>9</sup>

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

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.

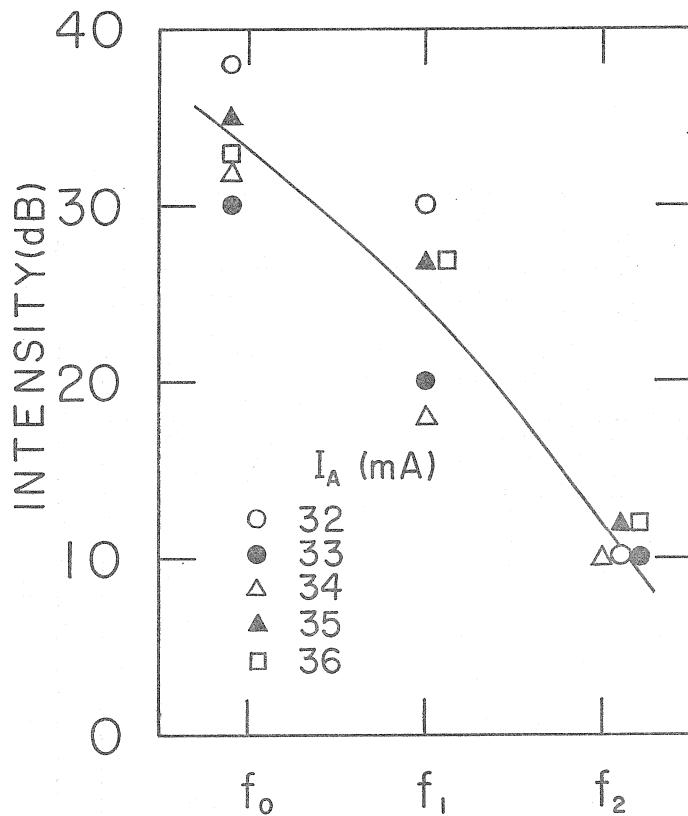


Fig. 4. Intensities of the harmonics of the oscillation in the case of Fig. 3. ObB is  $1\mu\text{V}$ .

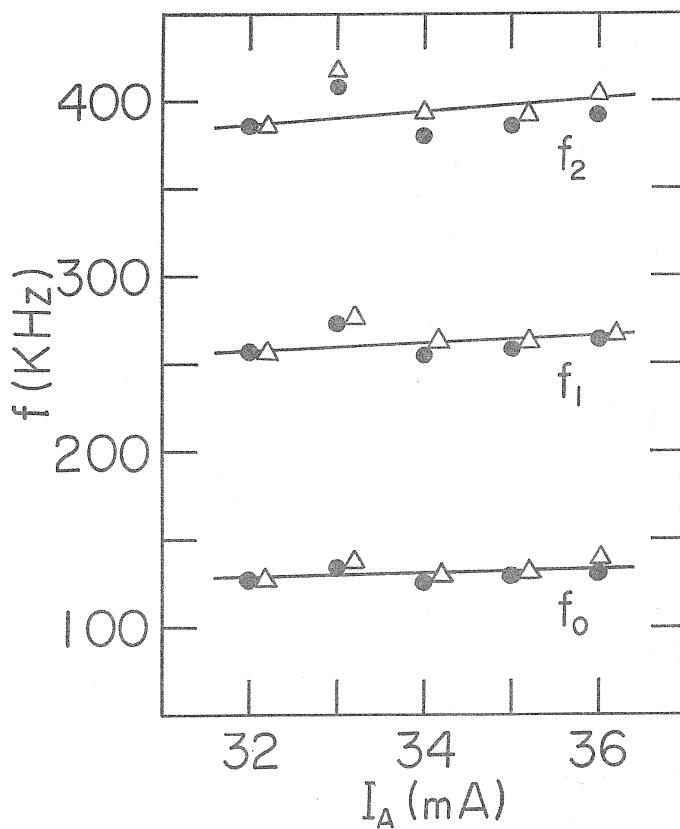


Fig. 3. Comparison of the observed frequencies with the calculated frequencies of ion oscillation.

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  $250\mu\text{A}$ .

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  $\mu$ A 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  $\mu$ A, 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 50  $\mu$ A, corresponding to the beam density of about  $1.7 \times 10^6 \text{ cm}^{-3}$ . Table II shows the results of probe measurements in this case. The electron temperature and

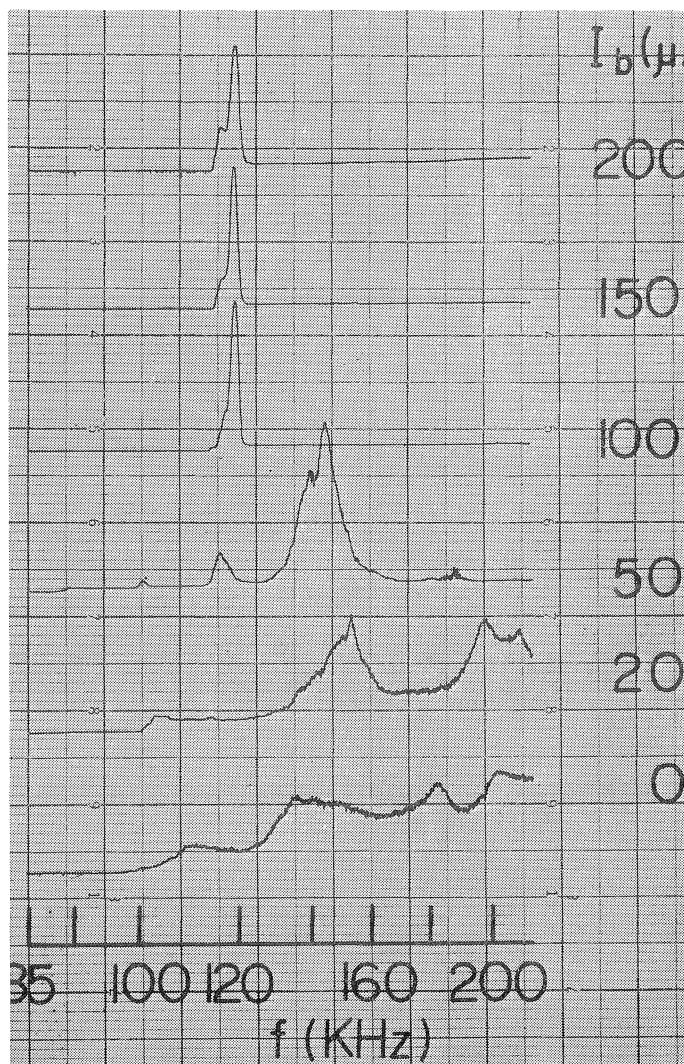


Fig. 5. Frequency spectra when beam current  $I_b$  is changed.

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.

| $I_b(\mu\text{A})$ | $T_e(\text{eV})$ | $V_p(\text{V})$ | $n_e(\times 10^7 \text{cm}^{-3})$ | $f_{pi}(\text{kHz})$ | $\lambda_D(\text{mm})$ |
|--------------------|------------------|-----------------|-----------------------------------|----------------------|------------------------|
| 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 electron beam, which seems to be ion oscillation, was observed. According to Briggs,<sup>10)</sup> the mutual interaction between a hot-electron plasma and a electron beam in the case of no-magnetic 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  $I_A=32\text{mA}\sim 36\text{mA}$  in Table Ib,  $\eta=2.8\sim 3.4\times 10^{-4}$ . 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<sup>11)</sup> have given the theory on this model, according to which the frequency is given by

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

where  $\lambda=4d$ ,  $2d$  being the width of the trough and  $\lambda_D$  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

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

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

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

from which  $f < 1.98 \text{ KHz}$ . 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.<sup>12)</sup> In our case, the spacing of the grid is only a little larger than the Debye length  $\lambda_D$  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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