J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 313–316

Effects of Ion-Beam Injection on Plasma Potential

HONZAWA Tadao
Department of Electric and Electronic Engineering,
Utsunomiya University, Utsunomiya 321-8585, Japan

(Received: 5 December 2000 / Accepted: 18 August 2001)

Abstract

It is experimentally shown that injection of a stationary ion beam always changes the background plasma potential in a beam-plasma system. In this experiment, a technique of ion energy analysis is adopted to determine the plasma potential in the system. Results indicate that the plasma potential changes sensitively depending on the beam-to-plasma density ratio, even if other parameters are not allowed to vary.

Keywords:
plasma potential, ion-beam, beam injection, energy analyzer

1. Introduction

How an ion beam affects the background plasma potential when it is injected into a plasma is a quite fundamental and very important problem in basic plasma physics. To our surprise, however, it remains an open question. In most experiments in which the ion beam injection is adopted, the change of the background plasma potential, induced by ion beam injection, has been neglected so far. However, the neglect of the plasma potential change is not justified in most cases, as shown below. In particular, the plasma potential change hinders the clarification of phenomena, caused by ion beams with low energies below 2 eV. In this paper, we wish to report experimental results on the changes of the background plasma potentials induced by injection of a stationary ion beam.

2. Experimental Methods

Experiments were carried out using a double plasma device [1-3]. In the device, two argon plasmas were produced by dc discharges. Plasma parameters were such as densities $N_e \simeq (1\text{–}5) \times 10^8$ cm^{-3}, electron temperature $T_e \simeq 2\text{–}3$ eV and ion temperature $T_i \simeq 0.1$ eV. Applying a dc voltage V_B to the driver plasma chamber, a stationary ion beam was injected into the target plasma through a negatively biased ($\simeq -90$ V) separation grid. Thus, an ion-beam-plasma system was formed in the target plasma region. In this case, the beam energy was controllable by changing the voltage V_B. The one-dimensionality of the ion beam was ensured by the plane grid with a large area.

In order to get information on the change of the background plasma potential in the presence of an injected ion beam, we measured the energy distribution of the plasma and beam ions by use of a gridded energy analyzer [4], movable along the axis (x-axis) of the chamber and noted the shifts of the peak positions of the plasma and beam ions in the ion distribution. Typical examples of a characteristic curve of the energy analyzer and the energy distribution of the plasma and beam ions are shown in Fig. 1. The peak voltages V_p and V_b in the distribution are defined as the corresponding background plasma and beam potentials, respectively. In addition, the ion currents I_p and I_b at voltages $V_p - \Delta V_c$ and $V_b - \Delta V_c$ (where $\Delta V_c = 10$ V) are defined as the total background plasma and beam ion currents in the system, respectively. Using these total

Corresponding author's e-mail: thonzawa@ml9.alpha-net.ne.jp

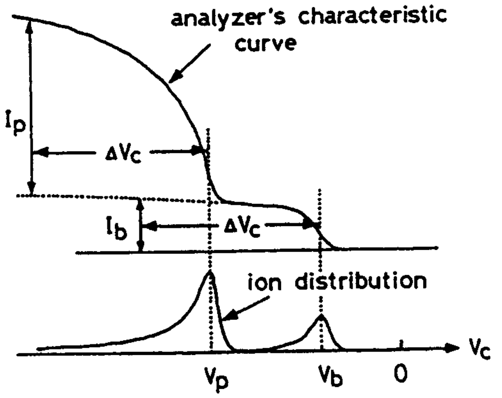

Fig. 1 Characteristic curve of ion energy analyzer and ion energy distribution. Here, the corresponding potentials V_p and V_b are defined. The total ion currents I_p and I_b are also defined.

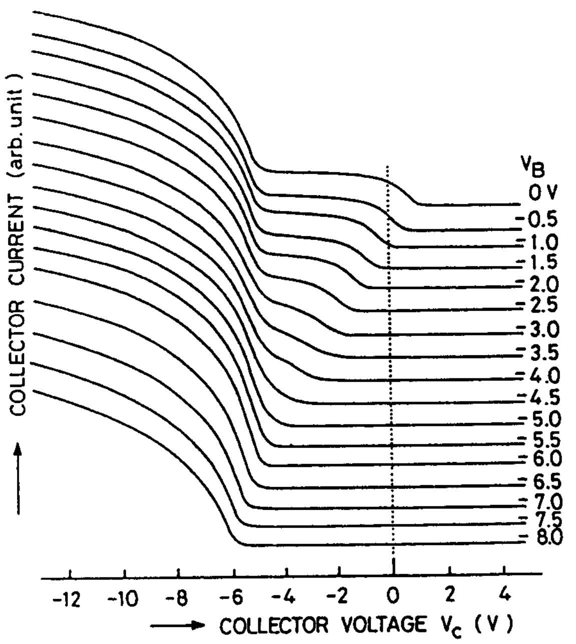

Fig. 2 Typical examples of the analyzer's characteristic curves changing with the change of V_B.

ion currents, the beam-to-plasma density ratio is determined such that $N_b/N_p \simeq I_b/I_p$.

The above method, determining the plasma potential V_p from an ion energy distribution, is particularly useful to know the change of the corresponding background plasma potential in the coexistence of both the plasma and beam ions. This is because under the effect of an ion beam the probe technique, being usually used to measure the plasma potential, is expected to present only an average value of the background plasma and beam potentials and not to give an accurate datum on the plasma potential. From this reason, most data of the plasma potentials were obtained from the ion energy distributions measured by use of a gridded energy analyzer in this experiment. Here, it is noted that in the case of no beam effect the plasma potentials V_p, determined from the ion energy distribution, were experimentally confirmed to be approximately proportional to the actual plasma potentials V_s, observed by the probe measurement, though the absolute values of V_p were lower by about 1.7 V than the ones of V_s. This means that $V_p \simeq V_s - 1.7$ V.

3. Experimental Results

3.1 Effect of Voltage V_B on Plasma Potential Change

By applying a DC voltage V_B between the two plasma chambers, an ion beam was injected into the target plasma from the driver plasma. Then, energy distributions of the background plasma and beam ions were measured by use of a gridded energy analyzer. Typical ion energy distributions, measured at various values of V_B, are shown in Fig. 2. From these observed distributions we can obtain the relations of V_p and V_b with V_B, as shown in closed circles and in crosses in Fig. 3, respectively. For comparison, the relation of V_p with V_B in the absence of the ion beam is also plotted in open circles in Fig. 3. Results in Fig. 3 clearly indicate that the beam injection induces a shift of V_p, whose value is changeable depending on the values of V_B.

3.2 Spatial Change of Plasma Potential

In the target plasma region, the intensity of an injected ion beam was observed to decrease with increasing x because of interparticle collisions. In addition, the background plasma density was greatly reduced in the sheath region close to the grid ($x \lesssim 2$ cm), because the grid was biased at a highly negative potential such as –90 V. Thus, the beam-to-plasma density ratio N_b/N_p changes with distance x. In the method described above, we could observe both the spatial changes of the potentials V_p and V_b at various x. Typical examples of the spatial variations of V_p with and without an injected ion beam are shown in closed and open circles in Fig. 4, respectively.

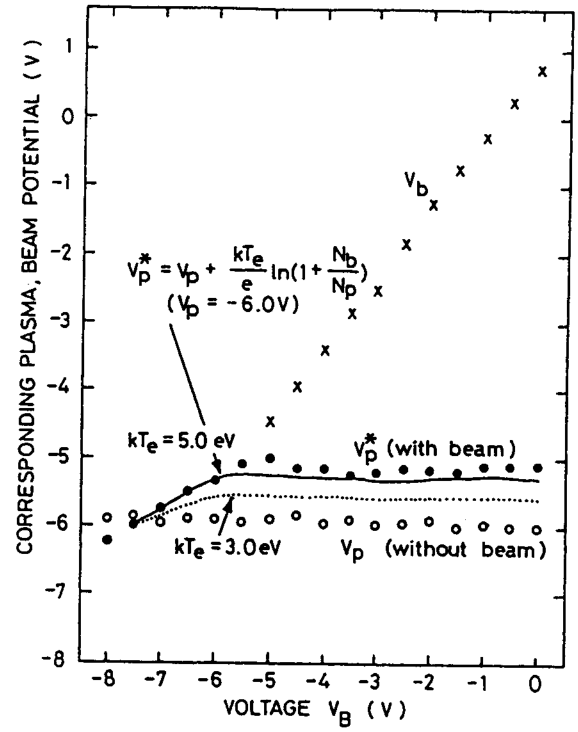

Fig. 3 Relations of the potentials V_p and V_b with V_B. Here, $V_p{}^*$ means the plasma potential with ion-beam injection.

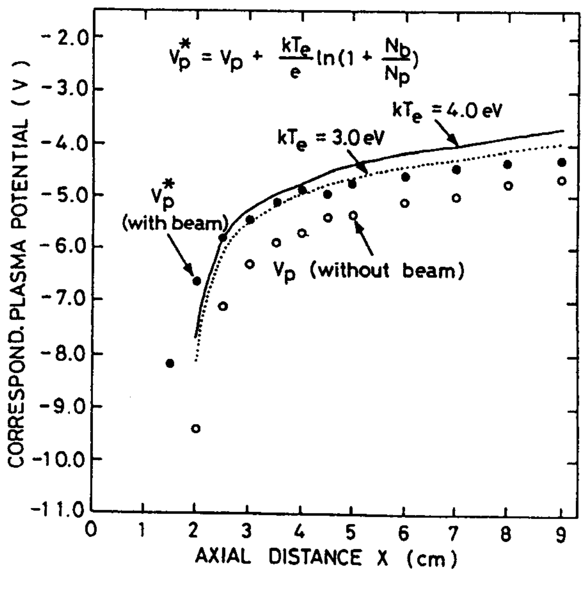

Fig. 4 Spatial variations of the plasma potential V_p with and without the beam effect.

3.3 Relation of Plasma Potential with Beam-to-plasma Density Ratio

In this experiment, we examined the dependence of the plasma potential V_p on the beam-to-plasma density ratio N_b/N_p by controlling N_p (observed at a fixed x), when N_b was invariable. The dependence is shown in Fig. 5. Here, the beam-to-plasma ion current ratio I_b/I_p, as defined in Fig. 1, is almost equal to the density ratio N_b/N_p.

4. Discussions and Conclusion

From the electron fluid equation of motion in a plasma, assuming the electron mass $m \to 0$, the Boltzmann relation is derived as

$$N_e = N_0 \exp(eV/kT_e), \tag{1}$$

where T_e, V, N_e and N_0 are the electron temperature, the plasma potential, the electron densities at V and at $V = 0$ V, respectively. e and k are the electron charge and the Boltzmann constant, respectively. In this paper, we try to apply eq. (1) to the body of a stationary plasma, assuming that it is not completely neutral. In other words, the relation is applied to the state of a sheath built between the stationary plasma and the surrounding wall. In such a case, we can say that V is regarded as the plasma potential seen from the wall. Under this

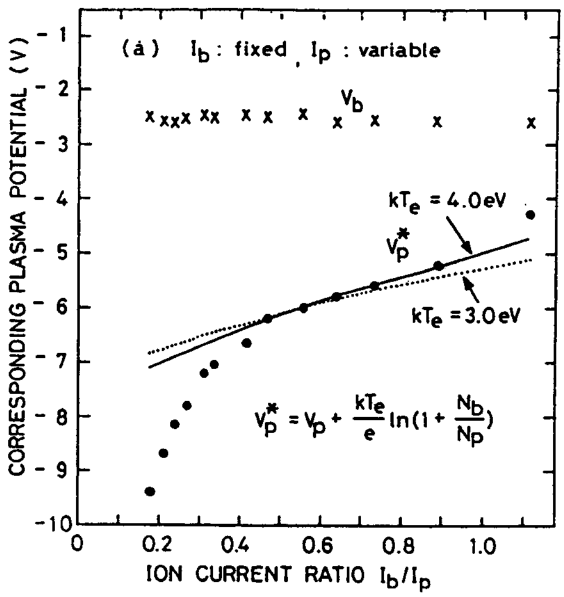

Fig. 5 Relations of the potentials V_p and V_b with ion current ratio I_b/I_p.

assumption, we have a relation as

$$N_p = N_0 \exp(eV_p/kT_e), \tag{2}$$

for the background plasma with a density N_p and a potential V_p, regarding the electron temperature uniform throughout the plasma. If an ion beam with a density N_b is injected into the plasma, then the plasma will have a different potential V_p* as follows. In this case, we have a relation as

$$N_p + N_b = N_0 \exp(eV_p^*/kT_e). \tag{3}$$

Here, plasma electrons with the same temperature are assumed to neutralize both the plasma and beam ions. So, we can find from eqs. (2) and (3) that the plasma potential is raised by

$$\Delta V = V_p^* - V_p = (kT_e/e) \ln (1 + N_b/N_p) \tag{4}$$

by the ion beam injection.

Based on this idea, we can explain almost all the experimental results obtained in this experiment. In Figs. 3, 4 and 5 theoretical curves are added in solid and dotted lines. Comparing experimental and theoretical results in Fig. 3, the solid line, where $kT_e = 5.0$ eV, is found to better fit the observed plots. The qualitative nature of the dependence on V_B can be explained by eq. (4), although $kT_e = 5.0$ eV, adopted here, is considerably higher than the observed value $kT_e \lesssim 3$ eV. Result in Fig. 4 is explained as follows. Using the value of $I_b/I_p \simeq N_b/N_p$ observed at each x, ΔV is calculated as a function of x, as shown in Fig. 4. Comparison of these results indicate that they are in good agreement with each other if $kT_e \simeq 3$ eV. Next, as seen from Fig. 5, the plasma potential V_p is found to change sensitively depending on the beam-to-plasma density ratio N_b/N_p even if V_B is fixed. The dependence of V_p on N_b/N_p has never been reported by anybody so far. Here, we try to explain this dependence with the help of eq. (4). In this case the better fit requires that $kT_e \simeq 4$ eV. In addition, the result suggests that another unknown cause is more effective for the change of V_p at small N_b/N_p.

References

[1] R.J. Taylor, K.R. MacKenzie and H. Ikezi, Rev. Sci. Instrum. **43**, 1675 (1972).

[2] R. Limpaecher and K.R. MacKenzie, Rev. Sci. Instrum. **44**, 726 (1973).

[3] T. Honzawa, Ch. Hollenstein, J. Vaclavik and Y. Kawai, Phys. Fluids **23**, 981 (1980).

[4] T. Honzawa, T. Sekizawa, Y. Miyauchi and T. Nagasawa, Jpn. J. Appl. Phys. **32**, 5748 (1993).