

Formation of Electric Potential in a Tokamak Edge by Limiter Biasing

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Abstract—It was found in the HYBTOK-II tokamak that the negative change of the electric potential of the plasma by a limiter biasing is influenced sensitively by the magnetic configuration in the SOL, but the positive change is not. The concept of “effective area” is introduced to explain the potential change due to a horizontal shift of plasma column in the negative biasing. Employing such a concept, a simple model for the formation of electric potential in a plasma for both a cold and an electron-emitting limiter is presented. It explains qualitatively the experimental results. The positive biasing was found to enhance the radial electric field at the scrape-off layer, and also at the inside, close to the last-closed magnetic flux surface, and seems to increase the particle confinement as measured by an increased line-averaged electron density with decreased H_α and impurity line intensities, along with a stabilization of the magnetic and electrostatic fluctuations.

I. INTRODUCTION

THE formation of electric potential in a tokamak has an increasing attractiveness in relation to the improvement of plasma confinement owing to the edge electric field. Recently, there have been reports on the effect of the electric field on the plasma turbulence and plasma confinement from both experiments [1]–[3] and theories [4]–[6].

The limiter biasing is one of the effective means to control the plasma potential. However, the physical mechanism for the potential formation in a toroidal configuration with closed magnetic surfaces has not been studied satisfactorily. In the present work a simple modeling for the determination of the electric potential in a plasma is proposed. This has a different point of view from the recent arguments on the generation of the radial electric field by an electrode bias [1] related to the cross-field current, poloidal rotation, and friction force. The model was compared with tokamak experiments with two different magnetic configurations due to the movement of the plasma column. In addition, a preliminary result of the effect on the electric and magnetic fluctuations is also presented.

II. EXPERIMENTAL DEVICES

A limiter bias experiment was performed on a small research tokamak, HYBTOK-II, whose top view is shown in Fig. 1 (a). The major and minor radii are $R = 0.4$ m and $b = 0.13$ m, respectively. A poloidal circular limiter made of molybdenum is installed near the pumping section. The limiter edge has a radius of $a = 0.11$ m and was powered by a charged capacitor

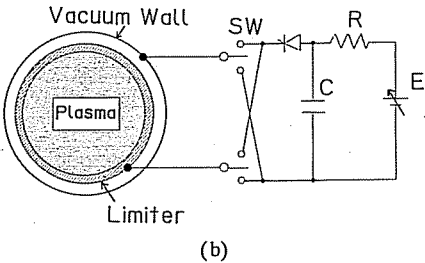
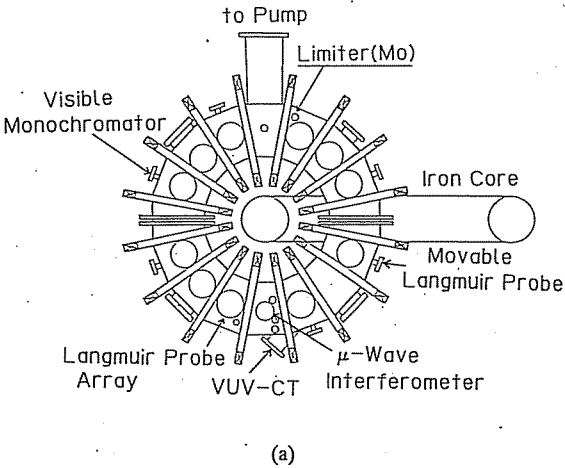


Fig. 1. Experimental devices: (a) top view of the HYBTOK-II tokamak machine; and (b) bias circuit ($R = 1$ k Ω , $C = 44$ mF, $E < 400$ V).

through a thyristor switch, as shown in Fig. 1(b). The main diagnostic equipment is the following: a movable Langmuir probe on the equatorial plane for a radial profile of edge plasma parameters, an array of Langmuir probes for a poloidal variation of plasma properties (as shown in Fig. 2), and a visible light monochromator for a hydrogen atomic line and an impurity behavior. Typical discharge parameters are: the toroidal magnetic field $B_t = 0.4$ T, the plasma current $I_p < 15$ kA, the loop voltage $V_{loop} \sim 5$ V, the line-averaged electron density obtained with a 70-GHz microwave interferometer $\bar{n}_e \sim 1 \times 10^{13}$ cm $^{-3}$, and the discharge duration $\tau_d \sim 10$ ms.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Potential Formation

Typical responses of discharge parameters to the limiter biasing are shown in Fig. 3 for a positive (Fig. 3(a)) and a negative (Fig. 3(b)) limiter voltage with respect to the chamber wall. The thyristor switch was turned on at $t = 5$ ms.

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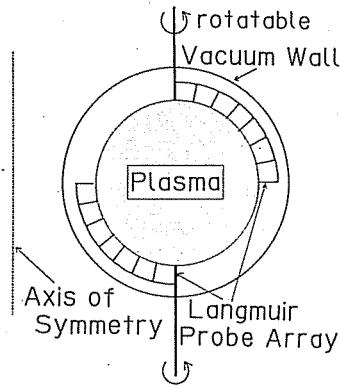


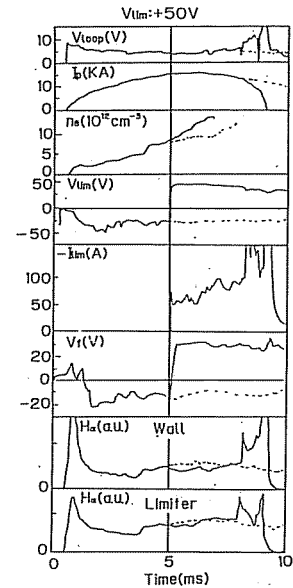
Fig. 2. Poloidal array of Langmuir probes.

Before biasing, the floating potential of the limiter is around -20 to -30 V. It goes to a specified potential and keeps its value by the capacitor during the tokamak discharge. A floating potential of a Langmuir probe at the edge shows a prompt increase when the limiter was biased positively. On the other hand, the floating potential changed slowly in time for the negative biasing. A positive change in plasma potential requires a loss of electrons. They have a very fast response time for the movement along the magnetic field lines. A loss of positive ion species to the negatively biased limiter tends to make the plasma potential negative. A transit time for protons with an energy of 10 eV at the edge is still short $60 \mu\text{s}$ for a toroidal circulation. Therefore the slow variation of V_f mentioned above is thought to be caused by other reasons. Here, it should be noted that the change of floating potential corresponds well to that of the plasma potential V_s , because $V_f \simeq V_s - 3T_e$, and $T_e(r)$ in the SOL was not affected much by limiter biasing, as shown below.

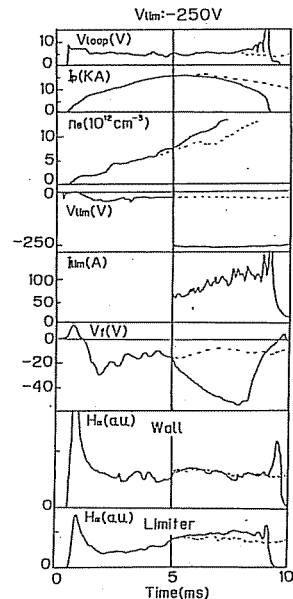
Changes of discharge parameters are plotted as a function of bias voltage in Fig. 4. A dependence of the limiter current on the bias voltage shown in Fig. 4(a) looks like those for an asymmetric double probe or a "large" Langmuir probe. The apparent area of the limiter ($\sim 1.4 \times 10^{-2} \text{ m}^2$) is much smaller than that of the chamber wall ($\sim 2.1 \text{ m}^2$). However, the effective area projected on the plane perpendicular to the magnetic field line,

$$A_{\text{eff}} = \left| \int (\mathbf{B}/B) \times d\mathbf{S} \right| \quad (1)$$

must be much smaller than the apparent one $|\int d\mathbf{S}|$ for the inner wall of the vacuum chamber, although that of the limiter is almost the same as the apparent area. The effective area for ions is different from that of electrons due to different dynamics in the sheath. However, for simplicity we do not take this into account. The ion current to the limiter saturates at the bias voltage of -100 or -150 V. But the electron current has a tendency to increase still at $+100$ V. These particle losses to the limiter corresponds well to the potential change at the edge as shown in Fig. 4(b). The positive limiter bias was limited below $+100$ V because of a disruption due to the substantial density increase shown in Fig. 4(c).



(a)



(b)

Fig. 3. Traces of discharge parameters for: (a) positive; and (b) negative limiter biasing.

In order to estimate the limiter current or a cross-field transport, we have to know the edge electric field E_r . A single Langmuir probe movable on the midplane was used to obtain the profile of the plasma potential as well as the electron temperature and density at the outside edge, as shown in Fig. 5. The electron loss was found to bring up very efficiently the plasma potential, while the negative biasing slightly decreased the positive E_r and did not change the sign of E_r . (see Fig. 5(a)). Due to an ion friction, a radial ion current is described as follows [7]:

$$j_{ir} = \frac{n_i e \nu_i r}{2} \left(\left(1 - \frac{4\omega_E}{\omega_{ci}} \right)^{-1/2} - 1 \right) \quad (2)$$

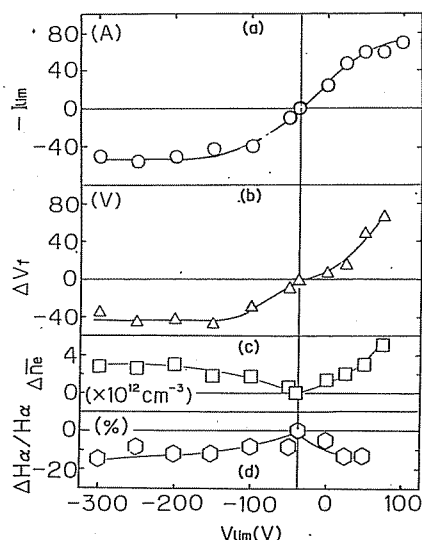


Fig. 4. Bias voltage dependence of: (a) limiter current; (b) change in floating potential of Langmuir probe in SOL; (c) change in line-averaged electron density; and (d) normalized change in H_{α} intensity.

where ω_E is the poloidal rotation frequency caused by an $E_r \times B_t$ drift, and is given by $E_r/(\tau B_t)$. Equation (2) shows a nonlinear increase when $\omega_E/\omega_{ci} > 0.1$ for a positive E_r . However, we have $\omega_E/\omega_{ci} \sim 1 \times 10^{-3}$ in the experiments of positive biasing. So the current increase in the positive biasing is not caused by the above-mentioned nonlinear increase of ion current. When $\omega_{ci} \gg \omega_E$ such as in the present situation, the radial ion current is proportional to the radial electric field. The conductivity is written as $\sigma_i = n_i \nu_i e^2 / (m_i \omega_{ci}^2)$. The ion current to the wall is estimated by this Ohm's law to be 1.4 A. It is much smaller than the observed limiter current, a few tens of amperes. Therefore the limiter current–limiter voltage characteristic curve cannot be described by the friction-induced ion current exactly perpendicular to the static magnetic field, (2). We have to consider some anomalous transport crossing the main magnetic field. For example, a turbulent fluctuation of the microscopic magnetic field is one of the candidates [8]. It gives a finite value for the connection length along the magnetic field between the limiter and wall.

In the above context, the position of the plasma column in the vacuum chamber gives an important effect on the magnetic configuration between the limiter and wall, although the data on Fig. 5 was taken at the time when the plasma was located at the right place. Fig. 6 gives two typical examples of the temporal change of the electric potential on a poloidal circumference associated with the change of plasma position for a positive (Fig. 6(a)), and a negative (Fig. 6(b)) biasing. The horizontal movement of the plasma column is shown at the top of each figure. The vertical movement is relatively small. The positive change of the plasma potential due to positive biasing is insensitive to the plasma position, while the horizontal column shift gives different time variations of plasma potential on in, out; top, bottom electrostatic probes in the negative biasing. A number written in the right side of each trace of V_f corresponds to the probe location shown in Fig. 6(c). Let us examine the negative biasing in detail. Just at

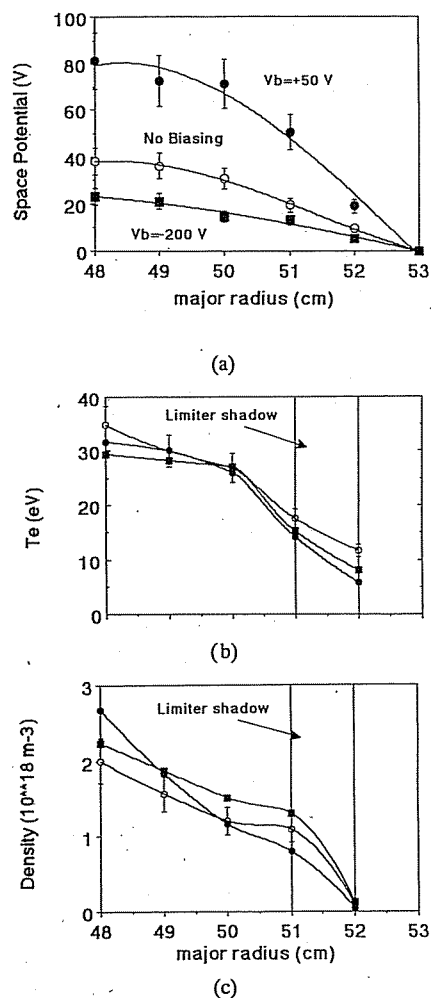
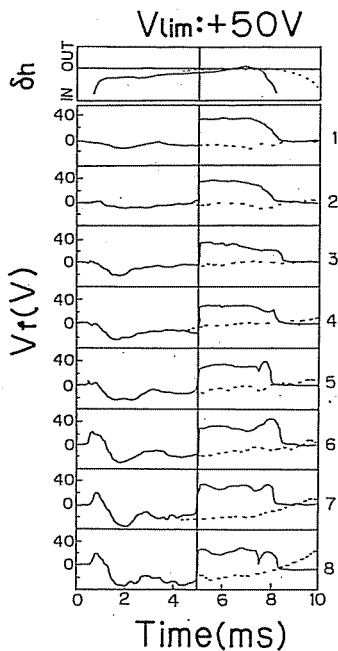


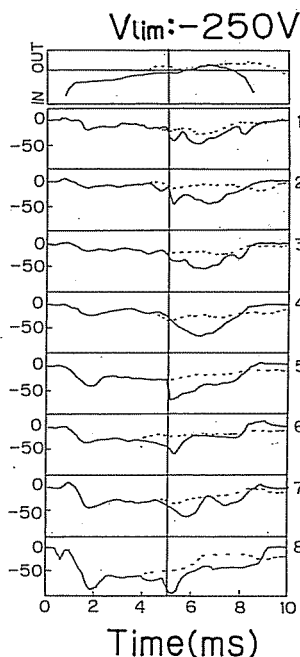
Fig. 5. Profile modification of plasma parameters at the edge by limiter biasing. Symbols of (●), (■), (○) correspond to positive (+50 V), negative (−200 V), and no biasing, respectively.

the moment of bias application, $t = 5$ ms, the plasma column was shifted inward. Negative changes were observed at the top (5,6), bottom (1,2), and inside (7,8). But the change at the outside (3,4) is relatively small. When the column moved to the center at $t \sim 6$ ms, the outside probes started to show a negative change, and almost all the potential of the probes went negatively except probe 6, due to an unknown reason. From $t = 6-7$ ms the plasma went slightly outside. Then the potential change of the inside probes became small, although those of the outside probes remained unchanged. Thus the potential change at the edge by a negative biasing is closely related to the horizontal position of the plasma column. We should note that the potential change here was emphasized by the horizontal movement of hot plasma, since V_f depends on the electron temperature as shown above. That is, for example, the inner probe touched a hotter plasma when the column shift was inward.

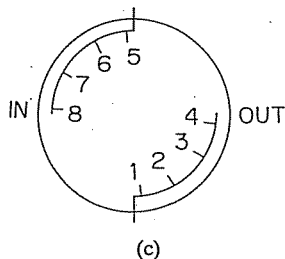
Summarizing the data of the probe potential at the edge between $t = 5$ and 7 ms for many shots, V_f is plotted as a function of horizontal displacement for the top (5), bottom (1), inside (8), and outside (4) probes in Fig. 7. Both the top and bottom probes show that the negative change becomes



(a)



(b)



(c)

Fig. 6. Time variations of floating potential of eight Langmuir probes for: (a) positive; and (b) negative biasing. Dashed lines show traces without biasing.

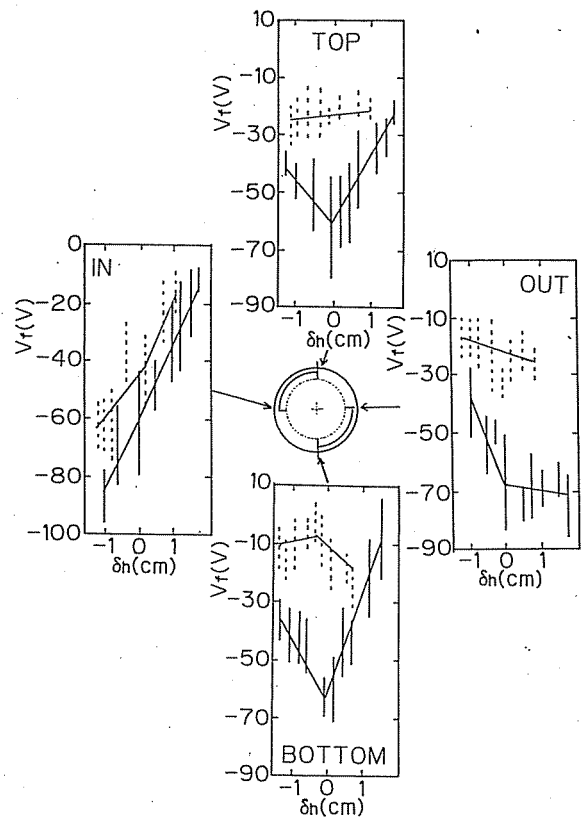


Fig. 7. Variation of floating potential due to the horizontal shift of plasma column. Solid vertical bars show the values for the negative (-250 V) biasing, and dotted vertical bars show those without biasing.

maximum when the plasma column is located at the center. The change becomes small when the plasma moves inward or outward. The outside probe shows a maximum change when the column shift is outward. It becomes small when the column displaces inward. The situation is completely opposite for the inside probe. From the above observations, it is predicted that a direct connection by magnetic field lines between the limiter and wall plays an important role for the formation of the electric potential by the limiter biasing.

B. Effects of Limiter Biasing on Tokamak Discharge

The effects of limiter biasing on the line-averaged electron density \bar{n}_e and H_α line intensity are shown, together with other discharge parameters in Fig. 3. With both biasing polarities, \bar{n}_e increased and the line-integrated H_α intensity on the horizontal plane, not seeing the limiter, decreased. The fact that the averaged plasma density increases with a decreased supply of neutral particles may suggest an improvement of particle confinement by the limiter biasing. However, the intensity of the H_α line coming from the limiter region increases for the negative biasing which has been said to be effective for the improvement of particle confinement [2], [3]. In addition, some impurity lines increase slightly, as shown in Table I. So it is not easy to say that the negative biasing improves the particle confinement. The observed increase of electron density may come from either a recycling at the limiter, or an impurity influx from that. The plasma potential did not go to

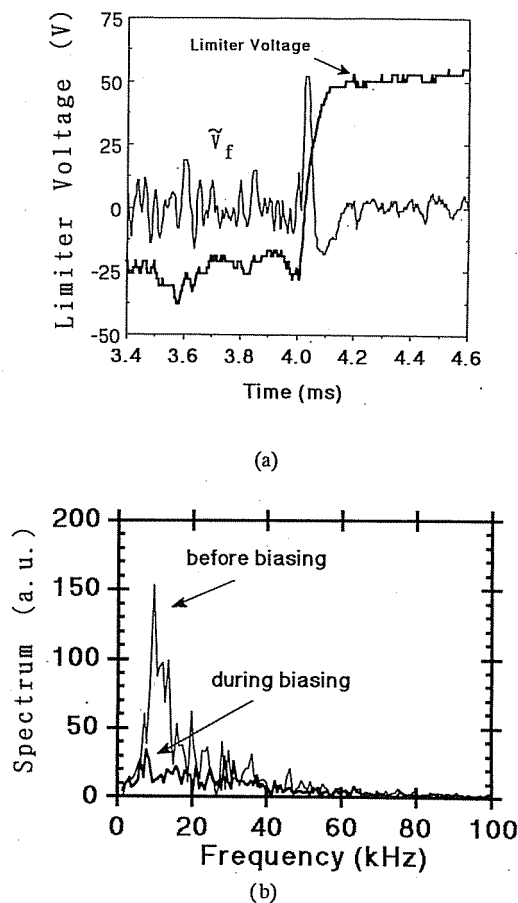


Fig. 9. Effect of the positive biasing on electrostatic fluctuation: (a) ac component of floating potential of a Langmuir probe located a little bit on the inner side from the limiter ($r = 11$ cm), shown by a thin line in arbitrary scale. The limiter voltage is traced by a solid line; and (b) frequency spectra of potential fluctuation detected by a probe located at $r = 8$ cm before (thin line) and during (solid line) positive biasing.

plasma column is shifted from the central position and the magnetic field lines are not parallel to the wall, but have a grazing angle with that. A conceptual schematics for such a situation is shown in Fig. 12. Fig. 12(a) corresponds to Fig. 11(a), while Fig. 12(b) does also to Fig. 11(b). When Fig. 12(a) is the case, the electric potential in the SOL plasma is well determined by the limiter potential. On the other hand, it becomes an asymmetric probe or a small single probe when the effective area of the wall becomes large, as in the case of Fig. 12(b). A core plasma potential is determined by an ion pressure gradient, a plasma rotation, and a cross-field transport, and also by the SOL potential as a boundary condition. If the former is not important, then the core plasma potential may be slid up or down by the potential of the SOL close to the core plasma. This is seen in Fig. 5(a). The electric field at the inner region $r \leq 10$ cm does not change by any biasing.

A poloidal rotation at the edge is induced by the thus produced electric field. The rotation gives an effect back to the electric field through the momentum balance equation. But these are not taken into account in the present model. A change in thickness of the scrape-off layer when the plasma is displaced may have a delicate effect on the potential formation. But it is neglected in the following qualitative model.

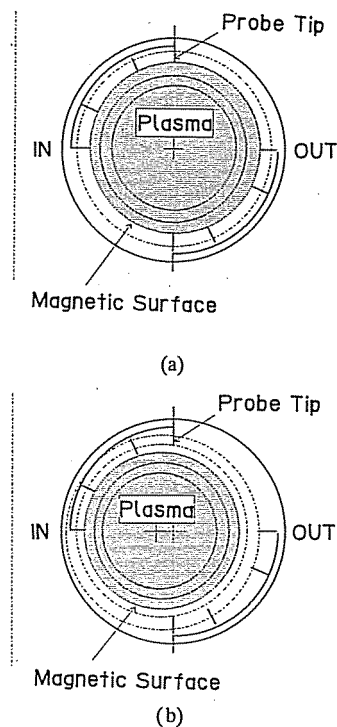


Fig. 10. Movement of magnetic surface due to the horizontal shift of the plasma column: (a) magnetic axis locates at the center; and (b) it shifts inward.

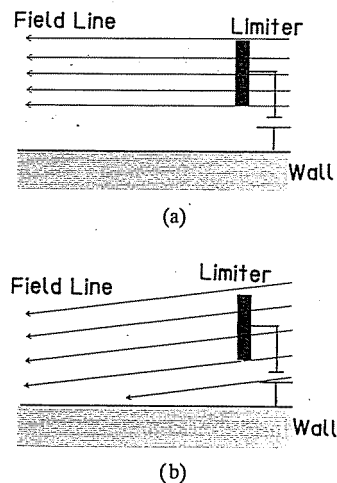


Fig. 11. Magnetic field lines in SOL: (a) when the plasma column takes a position at the center; and (b) when there is a shift of magnetic axis.

From the above considerations, a very simple model for determining the plasma potential is proposed below by taking into account the effect of the magnetic configuration on the effective area of the electrode on which an external voltage is applied. A model configuration is drawn in Fig. 13. A free plasma is assumed to be steadily produced by the rate G (ion-electron pairs/s), to be uniform in space, and to be consisted of singly ionized cold ions and electrons with the temperature T_e . S_k ($k = 1, 2$) is the effective area of each electrode whose potential is ϕ_k . Γ_{jk} is the flux of j th particle species to the k th electrode, which we assume to correspond to the limiter or wall in the real configuration. Both electrodes are connected to an external power supply of the electromotive

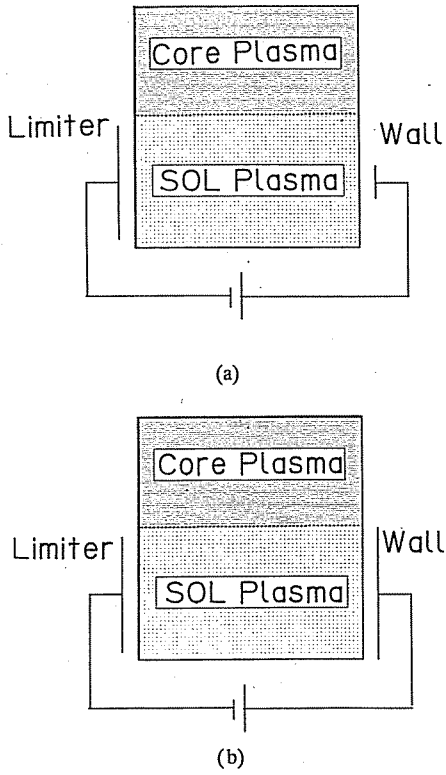


Fig. 12. Model configuration for plasma potential in SOL for: (a) the case where the magnetic field line goes parallel to the wall; and (b) the case where the field line crossing the limiter plate is connected to the wall.

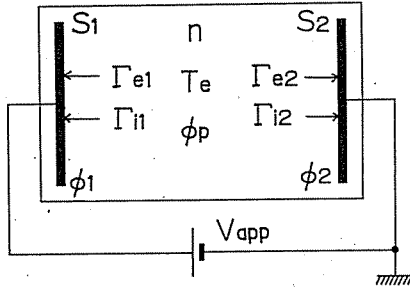


Fig. 13. Model for plasma potential formation. S_1 and S_2 are the areas of two electrodes corresponding to the limiter and the wall, respectively; ϕ_1 , ϕ_2 , and ϕ_p are the potentials of two electrodes and the plasma; V_{app} is the externally applied voltage between two electrodes; n and T_e are the plasma density and electronic temperature; Γ_{ek} and Γ_{ik} are the electronic and ionic flux to the k th electrode.

force V_{app} . The plasma container is assumed to be a perfect reflector for charged particles.

The ion or electron flux to each conducting electrode depends on whether the electrode potential is higher than the plasma potential ϕ_p or not, and is described as follows:

$$\Gamma_{ik} = \begin{cases} n \left(\frac{T_i}{m_i} \right)^{1/2} S_k, & (\phi_p > \phi_k) \\ 0, & (\phi_p < \phi_k) \end{cases} \quad (3)$$

$$\Gamma_{ek} = \begin{cases} \frac{n}{4} \left(\frac{8T_e}{\pi m_e} \right)^{1/2} S_k \exp\left(-\frac{\phi_p - \phi_k}{T_e}\right), & (\phi_p > \phi_k) \\ \frac{n}{4} \left(\frac{8T_e}{\pi m_e} \right)^{1/2} S_k, & (\phi_p < \phi_k) \end{cases} \quad (4)$$

where the numerical factor ~ 0.5 , coming from the presheath formation [9], is neglected in the expression for the charged-particle fluxes. As the particle decay rate on the k th electrode is Γ_{ik} , the particle balance equation is written by:

$$\frac{dn}{dt} = G - \Gamma_{i1} - \Gamma_{i2}. \quad (5)$$

In a steady state, we have $G = \Gamma_{i1} + \Gamma_{i2}$. The electric current flowing to the k th electrode is described by $I_k = e(\Gamma_{ik} - \Gamma_{ek})$. The current continuity gives the equation:

$$I_1 + I_2 = e(\Gamma_{i1} + \Gamma_{i2} - \Gamma_{e1} - \Gamma_{e2}) = 0$$

or

$$\Gamma_{i1} + \Gamma_{i2} = \Gamma_{e1} + \Gamma_{e2}.$$

From the potential relation, we have $\phi_1 - \phi_2 = V_{app}$. The plasma potential with respect to the no. 2 electrode which we will assume to be the wall, ϕ_{p2} is defined by $\phi_{p2} = \phi_p - \phi_2$. Then the voltage between the plasma and the no. 1 electrode is written by $\phi_p - \phi_1 = \phi_{p2} - V_{app}$. From these equations we can obtain the plasma potential ϕ_{p2} as a function of the applied voltage. But we divide the problem into the following two cases:

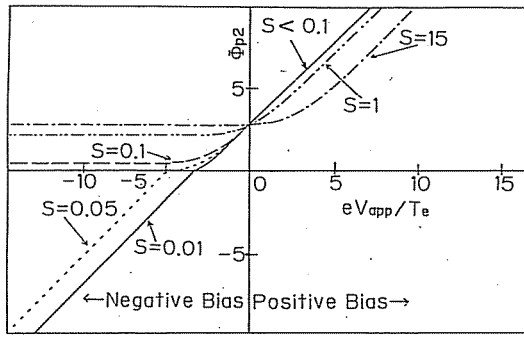
(a) $\phi_p > \phi_1, \phi_2$:

$$\Phi_{p2} = \ln \left(\left(\frac{m_i}{2\pi m_e} \right)^{1/2} \frac{\exp(\Lambda) + S}{S + 1} \right) \quad (6)$$

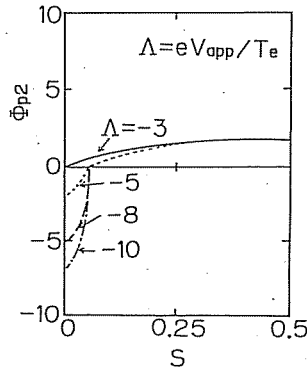
(b) $\phi_2 > \phi_p > \phi_1$:

$$\Phi_{p2} = \Lambda - \ln \left(\left(\frac{2\pi m_e}{m_i} \right)^{1/2} - S \right) \quad (7)$$

where $\Phi_{p2} = e\phi_{p2}/T_e$ is the normalized plasma potential, $\Lambda = eV_{app}/T_e$ is the normalized applied voltage, and $S = S_2/S_1$ is the ratio of the wall surface area to the limiter one. The normalized plasma potential is plotted as functions of the normalized applied voltage in Fig. 14(a), and of electrode area ratio in Fig. 14(b). In the former, $V_{app} > 0$ means the positive biasing, while $V_{app} < 0$ does the negative one. From these figures we understand that the plasma potential can be deep into negative when the effective area of the wall is enough small when compared with that of the limiter, because a small electron loss to the wall is compensated by the same quantity of ion loss to the limiter. On the other hand, when the ratio S increases, ϕ_{p2} remains positive, even by a deep negative biasing. In the limiter biasing experiments, a horizontal shift of the column position changes the inclination of the magnetic lines in the SOL with respect to the wall. It leads to a modification of the effective area of the wall. When a plasma column is situated at the central position in the vacuum chamber, the magnetic field line in the SOL is almost parallel to the wall. In this case the effective area should be minimum. In the present situation the effective area is not enough small to make the plasma potential negative. It may depend also on the magnitude of a magnetic field and a possible anomalous cross-field transport in the SOL. If the magnetic field increases, it would be possible to have a negative edge electric field. The



(a)



(b)

Fig. 14. Plasma potential estimated by a simple model: (a) change in the plasma potential by the applied voltage between nonemitting electrodes; and (b) the dependence on the ratio of areas of two electrodes.

effect of S on the negative biasing is summarized in Fig. 14(b), taking the normalized external voltage as a parameter. As is shown in Fig. 14(a), the positive biasing is not much effected by S . This is the reason why the positive biasing is insensitive to the horizontal movement of the plasma column.

An alternative candidate to achieve a real negative biasing is an injection of electrons. In the experiment, an electron-emitting cathode such as LaB₆ will be employed as the no. 1 electrode instead of the cold limiter. For the numerical estimate, the electron flux to the no. 1 electrode is modified as follows:

$$\Gamma_{e1} = \begin{cases} \frac{n}{4} \left(\frac{8T_e}{\pi m_e} \right)^{1/2} S_1 \exp\left(-\frac{\phi_p - \phi_1}{T_e}\right) - \gamma n \left(\frac{T_e}{m_i} \right)^{1/2} S_1, & (\phi_p > \phi_1) \\ \frac{n}{4} \left(\frac{8T_e}{\pi m_e} \right)^{1/2} S_1, & (\phi_p < \phi_1) \end{cases} \quad (8)$$

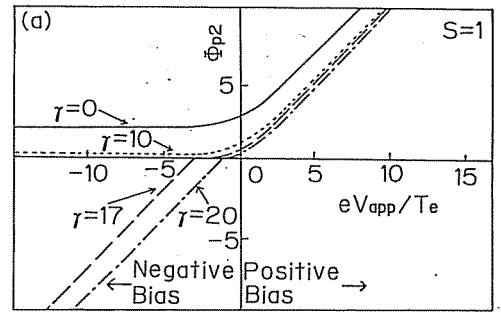
where γ is the measure of electron emission intensity. Then the plasma potential thus obtained becomes the following formulae:

(a') $\phi_p > \phi_1, \phi_2$:

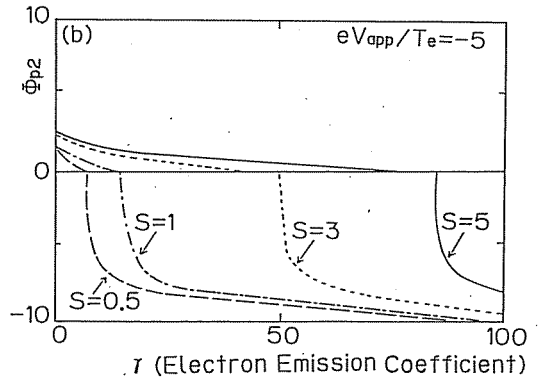
$$\Phi_{p2} = \ln \left(\left(\frac{m_i}{2\pi m_e} \right)^{1/2} \frac{\exp(\Lambda) + S}{1 + \gamma + S} \right) \quad (9)$$

(b') $\phi_2 > \phi_p > \phi_1$:

$$\Phi_{p2} = \Lambda - \ln \left((1 + \gamma) \left(\frac{2\pi m_e}{m_i} \right)^{1/2} - S \right). \quad (10)$$



(a)



(b)

Fig. 15. Plasma potential estimated by a simple model: (a) change in the plasma potential by the applied voltage between emissive and nonemissive electrodes; and (b) dependence on the electron-emission coefficient.

Numerical results are shown in Fig. 15. Even a moderate S value may have a negative potential if γ is large. In fact, an ion saturation current has a density of 0.5 A/cm² when the plasma density is 10¹² cm⁻³ and the electron temperature is 15 eV. A LaB₆ cathode has an emission of more than 10 A/cm². Then we have $\gamma \gtrsim 20$. Fig. 15 may give us a chance to succeed a negative biasing.

V. CONCLUSIONS

In a limiter biasing experiment in the HYBTOK-II tokamak the negative change of plasma potential is influenced sensitively by the magnetic configuration in the SOL between the limiter edge and the wall, but the positive change is not done so much. The concept of "effective area" corresponding to the surface area of the electrode projected to the plane perpendicular to the magnetic field is introduced. A horizontal shift of the plasma column from the central position in the vacuum chamber increases the effective area of the wall. Employing such a concept, a simple model for the formation of the electric potential in a plasma is presented. It is shown that the area ratio of two electrodes corresponding to the wall and the limiter is a key parameter in obtaining a negative potential. Experimental results can be explained qualitatively by this model. In addition, it is also pointed out that an electron-emitting cathode instead of the cold limiter is very helpful in obtaining a negative-edge electric field.

The positive biasing was found to enhance the radial electric field E_r at the edge. The enhancement of edge E_r is not

confined in the SOL, but is penetrated into the interior by much more than the ion Larmor radius. The physical mechanism is not clear. The positive biasing seems to increase the particle confinement because of an increased line-averaged electron density with a decreased H_α and impurity intensities, along with a stabilization of magnetic and electrostatic fluctuations. On the other hand, we cannot conclude anything of the tokamak discharge for the negative biasing, probably because we cannot obtain a negative E_r at the edge by the present cold limiter.

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