Plasma Potential Measurement in Detached Plasmas by Emissive Probe Considering Space-Charge-Limited Effect

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The accuracy for the measurement of the plasma potential was improved using an emissive probe (EP) considering the space-charge-limited (SCL) effect. To validate the measurement method, the plasma potential measured using a method combining double probe (DP) and single probe (SP) was compared to the developed method. The two measurement methods showed a good agreement: it was confirmed that the EP considering the SCL effect was able to measure the plasma potential accurately even in detached plasmas with a high-temporal-resolution.

Keywords: detached plasma, plasma potential, emissive probe, double probe, space-charge-limited effect

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Plasma detachment is an effective method to reduce the heat load flowing into the divertor target [1, 2]. The plasma is cooled down by promoting radiation loss through the significant interactions between plasma and neutral gas. As a result, a low-temperature volume-recombining plasma which is detached from the target plate is generated. To understand the detached plasma formation, detailed measurements of plasma parameters such as electron temperature T_e, electron density n_e, and plasma (space) potential V_s are needed [3].

In particular, T_e and n_e are quite important parameters for plasma-gas interactions. However, it is known that the single Langmuir probe (SP), which is one of the most convenient techniques, basically overestimates the T_e value in the detached plasma [4]. In the recent research performed in the linear plasma device NAGDIS-II, T_e and n_e obtained by the double-probe (DP) measurement show good agreements with those by the laser Thomson scattering even in low-temperature (T_e <1 eV) detached plasmas [5].

By using the T_e estimated by DP and the floating potential V_f measured with SP at the vicinity, V_s can be also measured in the detached plasma (hereafter called "DSP" technique) [6]. Furthermore, by using the statistical analysis technique called the conditional averaging (CA), time evolution of V_s during the intermittent plasma-ejection event was revealed with high-temporal resolution (~μs) [7]. This reported that V_s has important roles for determining azimuthal and radial motions of coherent structures. However, the CA method can only extract one averaged intermittent event, and thus statistical techniques assuming stationarity (e.g., Fourier and correlation analysis) cannot be applied for the CA result.

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This study, therefore, aims to establish another V_s measurement method which can directly obtain time-resolved signal with high accuracy without any statistical technique like CA analysis. One of the famous V_s measurement techniques is the emissive probe (EP) [8] which essentially has the high-temporal resolution. By comparing V_s from EP and that by DSP without high-temporal resolution, an importance of considering the space-charge-limited (SCL) effect was indicated for the accurate V_s measurement. After that, we will suggest a measurement system of the time-resolved V_s considering the SCL effect.

The tip of the EP is filament shape, as shown in the inset of Fig. 1 (a). The typical length of the EP tip is 2 mm, and filament material is 0.1-mm-diameter tungsten. To heat the EP tip, DC bias is applied between points "a" and "b" in the inset. The black and red horizontal dashed lines in Fig. 1 (a) indicates V_f and V_s, respectively, measured by another single probe in attached plasma. It is confirmed that V_f of EP gradually shifts to V_s by increasing the heating current I_h as the thermoelectric emission from the EP. However, the EP measurement has following problems.

The heating voltage V_h, which is used to heat the EP tip, causes a potential difference between points "a" and "b". This difference affects the potential measurement accuracy. Thus, we introduced a switching circuit, which was also used previously to measure negative ions [9], to turn on/off the heating current by using transistors. Only when they were turned on, the heating current was flowed into the probe tip. Figure 1 (b) shows an example of the time series of the potentials at point "a" and "b". The potential difference at point "a" and "b" corresponds to V_h. At the time without heating, the voltage difference becomes zero. After stopping the heating, due to a decrease of the filament temperature, thermoelectric emission and floating

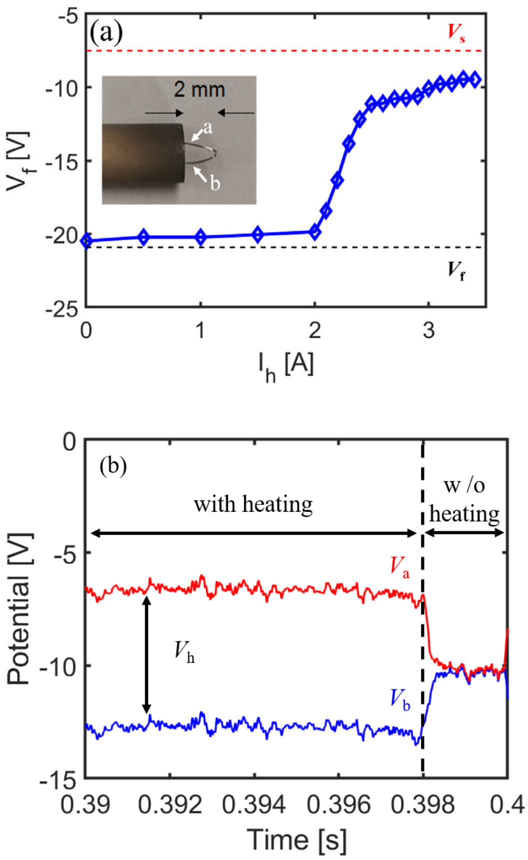

Fig. 1 (a) Floating potential V_f of EP as a function of the heating current I_h. Inset shows the photograph of the EP. (b) The floating potentials of the EP tip at points "a" and "b".

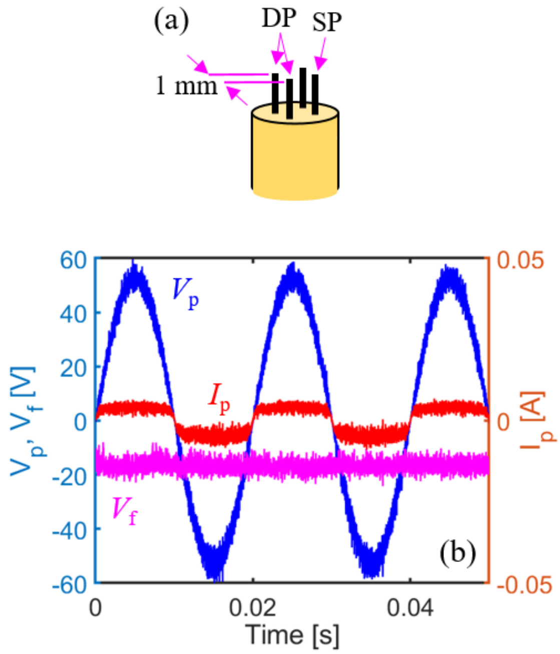

Fig. 2 (a) A schematic of the DSP and (b) typical time-series data of DSP. Here, V_p and I_p are measured by DP and V_f is measured by SP.

potential decrease after ~10 ms. Therefore, before the decrease of the potential, V_h is turned on again in this research. Besides, the first 0.5 ms data from turning off time were eliminated for the potential measurement to consider the switching delay.

Figure 2 (a) shows the schematic of DSP. Each electrode is 1 mm long and 0.5 mm in diameter, and the distance between each electrode is designed to be 1 - 3 mm. In the DSP method, T_e is evaluated using two electrodes as a double probe (DP), and V_f is measured using another electrode as SP. It has been confirmed that DP can measure T_e even when there is the plasma potential fluctuation which leads to overestimation of T_e measured by SP in detached plasmas [10]. It is inferred that the magnetic field effects are not critical for the DSP with an additional SP because the electrodes distance was much larger than the sheath thickness estimated by Child-Langmuir law [11].

Figure 2 (b) shows the time-series data of the DSP method. The probe bias V_p and the probe current I_p are obtained from DP, and T_e is evaluated from the I_p-V_p characteristic. The V_f value is obtained from SP without biasing. By using obtained T_e and V_f, V_s can be evaluated from Eq. (1).

$$V_s = V_f + \alpha T_e \text{ [eV]}. \tag{1}$$

Here, $\alpha \sim 4.0$ in helium (He) plasma.

In this study, we measured He plasma parameters in the linear device NAGDIS-II [12]. The experimental conditions are as follows: the discharge current, I_{dis}, was 20 A, and magnetic field strength, B, was 0.1 T. Measurement axial position, z, was 1.40 m from the anode position along the device. Under these conditions, the neutral gas pressure dependences of V_s were investigated by EP and DSP methods.

In the EP measurement, the neutral gas pressure was continuously changed from 6.3 to 25 mTorr. The EP filament was heated at the current of 3 A. The switching circuit turns on/off the heating current at a frequency of 10 Hz with a duty ratio of 95%.

The probe bias of the DSP was swept between ±40 V with the sweeping frequency of 50 Hz. The plasma potential V_s was calculated according to Eq. (1) from the electron temperature T_e and the floating potential V_f at each neutral gas pressure.

As the neutral gas pressure increased, the plasma at the measurement position changed from attached to detached plasmas, so the purpose of this experiment is to confirm whether the EP measurement could give similar results as with the DSP even when the plasma became detached.

We first compared the neutral gas pressure dependence of the plasma potential measured with EP and DSP, as shown in Fig. 3. Solid line and dashed line with circle show the results of EP and DSP, respectively. It is seen that the EP deduced lower value than that from DSP method.

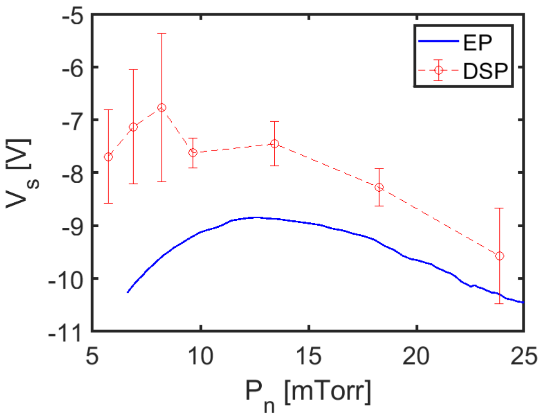

Fig. 3 Neutral gas pressure dependence of V_s measured with normal EP (solid line) and DSP (dashed line with circle).

This reason is thought to the space-charge-limited (SCL) effect. In previous study, the floating potential was perfectly consistent with the plasma potential even with sufficient heating of the EP, and the effect of SCL was discussed [8]. It is known that the plasma potential V_s can be expressed using the floating potential with the heating V_f^{heat}, and the electron temperature T_e as follows:

$$V_s = V_f^{heat} + \beta T_e \text{ [eV]}, \quad (2)$$

where β is equal to 0.99 in He plasma. The floating potential of the EP increases with the thermoelectron emission and approaches to the plasma potential. However, with increasing the thermoelectron emissions, a potential barrier is produced due to the piled electrons near the probe. Hence, the barrier suppresses the amount of thermoelectron emission (space-charge-limited) and the potential can approach a certain value. The value of βT_e was theoretically calculated in Ref. [13].

Therefore, in order to measure the plasma potential accurately, it would be necessary to consider the term of βT_e. To measure T_e with EP, we used the relationship between V_s and V_f in Eq. (1). Here, by using EP, V_f can be easily obtained without the heating. From Eqs. (1) and (2), T_e can be derived by

$$T_e = (V_f^{heat} - V_f)/(\alpha - \beta). \quad (3)$$

The accuracy of T_e measurement from Eq. (3) in recombining plasmas has been already demonstrated in previous studies by comparing with a spectroscopic method [14, 15]. In this study, by substituting T_e obtained from Eq. (3) into Eq. (2), V_s was measured and then compared with DSP results.

To acquire the floating potentials with heating V_f^{heat} and without heating V_f at the same position, EP measurement was performed twice. Figure 4 (a) indicates the results of V_f^{heat} and V_f. It is found that V_f^{heat} is higher than V_f particularly in low neutral gas pressure case. It should be noted that high-temporal-resolution V_s evaluation cannot be performed in this case, because V_f^{heat} and V_f are measured separately.

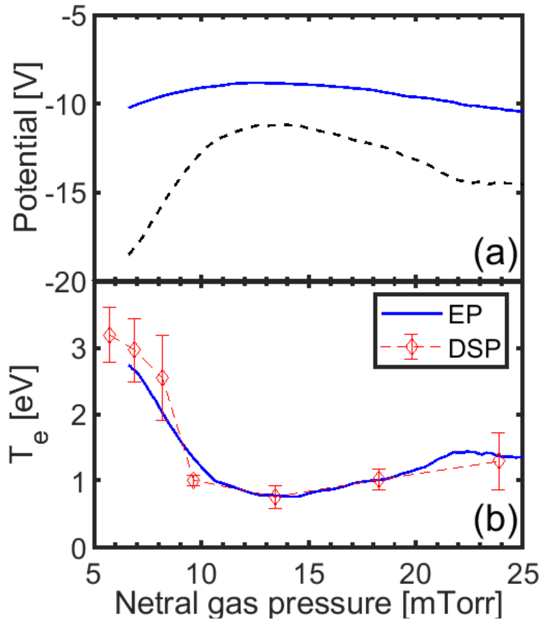

Fig. 4 (a) V_f^{heat} and V_f measured with EP with (solid line) and without the heating (dashed line), respectively. (b) Neutral gas pressure dependence of T_e evaluated from EP (solid line) and DSP (dashed line with circle).

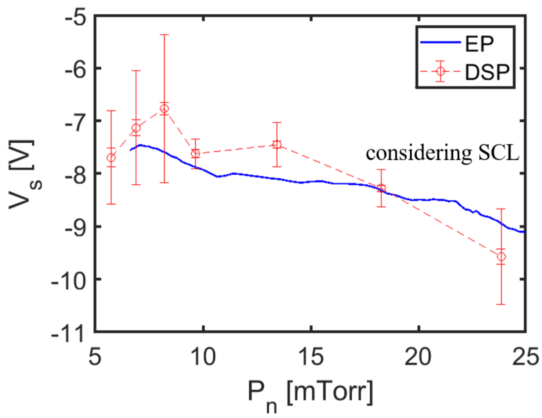

Fig. 5 Neutral gas pressure dependence of V_s measured with EP considering SCL (solid line) and DSP (dashed line with circle).

Figure 4 (b) shows the T_e calculated by substituting V_f^{heat} and V_f into Eq. (3). In addition, T_e measured with DSP is overplotted. The 95% confidence interval is used as error bars. It can be seen that T_e obtained from two methods show good agreement. By increasing the neutral gas pressure, T_e decreases from ~3 eV to ~1 eV.

Figure 5 shows V_s calculated by substituting T_e in Fig. 4 (b) into Eq. (2). Two measurement results show good agreement similar to T_e. This indicates that the EP considering SCL method can evaluate the plasma potential

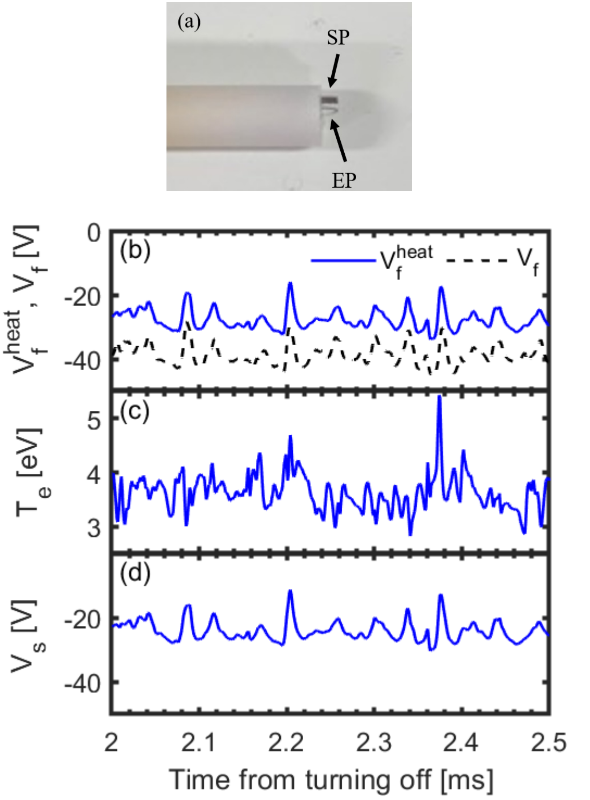

Fig. 6 (a) Photograph of EP with an additional SP. (b) Time series of (b) V_f^{heat} (solid line), V_f (dashed line), (c) T_e, and (d) V_s.

with a high accuracy even in low-temperature plasmas with $T_e \sim 1$ eV.

To understand high-speed phenomena such as transport in detached plasma, it is important to know the dynamics of plasma potential. To obtain the time-resolved V_s, simultaneous measurement of V_f^{heat} and V_f is needed. For this purpose, we would like to suggest a new probe consisting of EP and SP as shown in Fig. 6 (a). Figures 6 (b, c, d) shows an example of measurement results as a function of time. In these figures, the time series from 2 to 2.5 ms from the turning off time is plotted, where the turn off period was 5 ms and the sampling frequency was 1 MHz. Figure 6 (b) shows V_f^{heat} and V_f measured simultaneously, using the EP and SP, respectively. It is seen that the EP always deduced higher potential than the SP roughly by 12 V. Figure 6 (c) shows the electron temperature obtained from the difference between V_f^{heat} and V_f in Fig. 6 (b). The temperature evolution ranged at 3 - 5 eV. It seemed that the temperature increased in response to increase in the potential. Figure 6 (d) shows the plasma potential measured with EP considering SCL method. The standard error of the T_e and V_s were approximately 0.35 eV and 2.5 V, respectively. The potential fluctuated with positive spikes with height of more than 10 eV from the base potential of ∼−25 eV.

The time series data of the plasma potential obtained in this way can be useful for measuring a transport phenomenon. In the future, we plan to validate the measurement accuracy of the newly developed probe by comparing with conditional averaged DSP results and then apply to elucidate mechanism of intermittent radial transport in detached plasma [6].

To establish a high-temporal resolution measurement which can directly obtain the plasma potential without any statistical technique like CA analysis, we improved the emissive probe measurements. We conducted the plasma potential measurement using an emissive probe considering space-charge-limited (SCL) effect, and the values were compared with double probe and single probe equipped on the probe head (DSP) method. The emissive probe considering the SCL effect result was good agreement with DSP result. We plan to apply this method to intermittent transport in detached plasma in the future.

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