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Emissive probe measurement of electron temperature in recombining plasma produced in the linear divertor simulator TPD-II

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Abstract

Emissive probe (EP) measurement of the electron temperature T_e, which was proposed by Shindo et al. [Rev. Sci. Instrum. 59 (1988) 2002] is applied to the measurement of T_e in the detached recombining plasma produced in the linear divertor simulator. In the determination of T_e by the EP method, we consider application limits based on the space-charge-limit effect studied by Ye and Takamura [Phys. Plasmas 7 (2000) 3457]. We have observed that as neutral pressure is increased for developing the plasma detachment, T_e obtained with the EP decreases from a few eV to 0.4 eV, on the other hand, the Langmuir probe (LP) method gives anomalously high T_e of 3–9 eV. The EP method yields more reliable value of T_e than the LP method does. The electron temperature obtained through the spectroscopic method is also shown.

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1. Introduction

The measurement of the electron temperature, T_e, in a gaseous divertor is important in order to investigate the plasma detachment in the divertor, because T_e relates directly to the rate coefficient for the recombination process. To measure T_e in recombining plasma resulting from a gaseous divertor regime, electrostatic Langmuir probes (LPs) and spectroscopic methods are usually employed. However, it has become known that these two methods produce T_e values that differ from each other by an order of magnitude [1–3]. The values of T_e obtained by the LP have been much higher than those obtained by spectroscopic method. Such a discrepancy can be found not only in linear divertor simulators but also near the divertor plate in magnetic confinement devices [3].

The cause of the discrepancy has been pointed out to be an overestimation in the LP measurement [2]. Such an overestimation can arise from two sources. One is the electric resistance in the plasma, and the other is plasma fluctuation. For the former case, when the electric current drawn by the probe passes through the plasma, voltage drop appears along the path because of the plasma's electrical resistance. The amount of voltage drop is unintentionally added to the LP current–voltage (*I–V*) characteristic. Consequently, the *I–V* characteristic becomes gradual, and thus T_e is overestimated. On the other hand, plasma fluctuations can also make the

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slope of the *I*–*V* characteristic gentle, thus also overestimating T_e. This is known to be a difficulty with probe measurement in rf plasmas.

In order to avoid the influence of resistance, we should employ a means of probe measurement that does not induce current in the plasma. An electrically floating emissive probe (EP) effectively cancels out the current. EPs have usually been employed to measure the plasma space potential. Shindo et al. proposed the use of the EP to measure T_e for processing plasmas [4]. Therefore, here we investigate the application of the EP to measure T_e for the recombining plasma in a gas divertor.

In this paper, we will examine the validity of the Shindo formula for estimating T_e by referring to the effect of the space-charge limit studied by Ye and Takamura [5], and we will present the electron temperatures experimentally obtained with the EP for various values of neutral gas pressure. We also compare the electron temperatures thus obtained with those obtained through the two other methods, i.e., a single LP and the spectroscopic method.

2. Experimental setup

The experiment was carried out in the linear divertor simulator TPD-II at the National Institute for Fusion Science (see Fig. 1(a)) [6,7]. Helium plasma was continuously generated by a dc discharge between the anode and the LaB_6 cathode. It can be seen from Fig. 1(a) that the plasma goes into the simulated edge plasma region (E region) and then into the divertor region (D region). An orifice 20 mm in diameter, somewhat larger than the plasma diameter, is located 0.7 m from the target. This orifice serves as a baffle for the closed divertor in confinement devices [6]. The machine can produce high-density plasma 10^{19}–10^{20} m^{-3} in electron plasma density n_e and several eV in electron temperature T_e for a discharge current I_d of 100 A and for an axial magnetic field of several kG [7].

The neutral gas pressures at regions D and E, P_D and P_E, were measured by using baratron gauges located in the corresponding regions. In order to develop plasma detachment, the value of P_D was varied between 0.4 and 100 mTorr by adjusting the flow rate of the helium neutral gas, Q_{He}^{END}, injected from the end of the machine. As P_D was greater than ~10 mTorr, the recombining plasma clearly appears at the position of the probes.

Note that in this experiment, in order to reduce the plasma heat flux and to avoid damage to the EP, I_d was reduced to 35 A. Furthermore, the flow rate of the helium neutral gas injected into the plasma source for the discharge was adjusted to relatively high. Then, the partially recombining plasma can already be seen in the E and D regions, as shown schematically in Fig. 1(a), even if Q_{He}^{END} is zero (in this case, P_D and P_E were 0.4 and

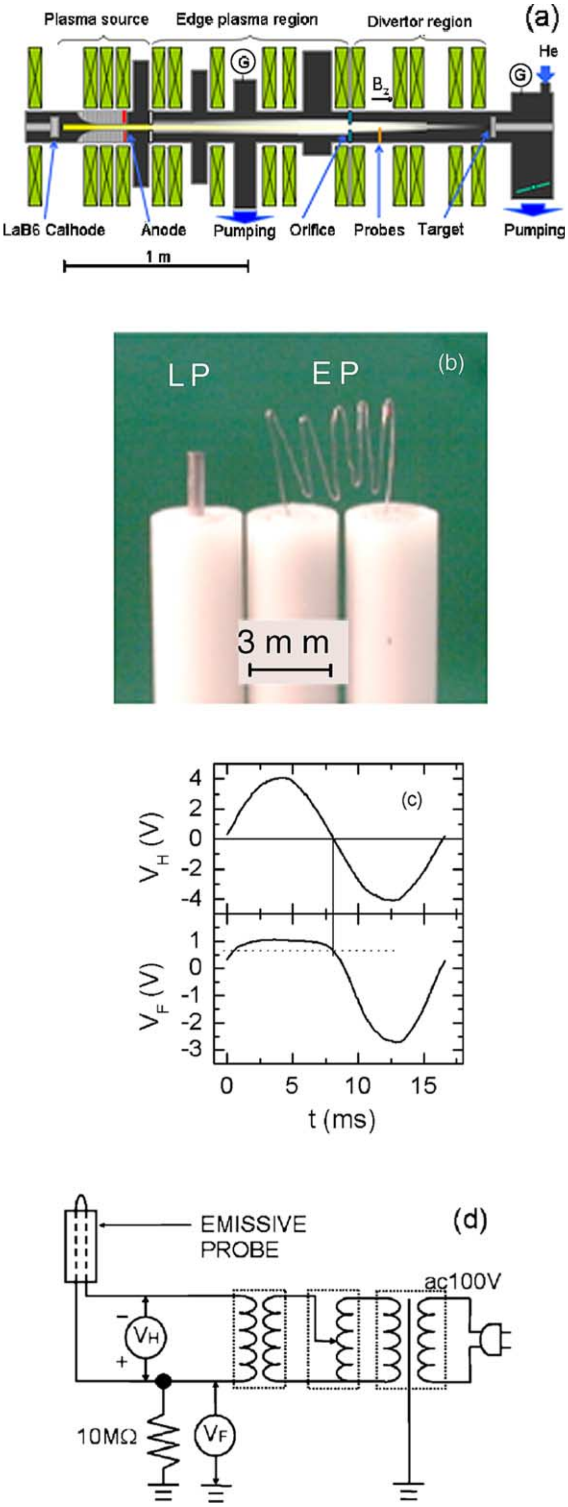

Fig. 1. Experimental setup. (a) Schematic diagram of TPD-II, (b) EP and LP, (c) the heating voltage V_H and the floating potential V_F of the EP, and (d) schematic diagram of the EP circuit for T_e measurement.

5.5 mTorr, respectively). Thus, the value of n_e was reduced by less than 10^{17} m^{-3}. [1]

The probes, i.e., the EP and the single cylindrical LP, were both located in the D region (see Fig. 1(a)). The probe filament of EP was made of tungsten and was 0.05 mm in diameter and 30 mm long (see Fig. 1(b)). The electrode tip of the LP was tungsten also, 0.5 mm in diameter and 2 mm long.

3. Method of the EP measurement of T_e

The EP circuit employed in this experiment is schematically shown in Fig. 1(d). The filament was heated by a sinusoidal current of 60 Hz. In this situation, the potential drop along the filament, V_H, varies under the thermoelectron emission, and the floating potential of the EP, V_F, varies as shown by the bottom layer in Fig. 1(c).

The variation of V_F, which was utilized for estimating T_e, has been interpreted by Shindo et al. [4]. As mentioned above, as the current passes through the filament, the potential changes along the length of the filament. Then, the current drawn from the plasma varies according to the position along the filament. The total current drawn by the EP, I_{EP}, is the summation of the current drawn by each position, so that,

$$I_{EP} = \frac{S}{V_H} \int_{V_F^+ - V_H}^{V_F^+} (j_p + j_{em}) \, dV_\ell, \tag{1}$$

where V_ℓ is the potential at a portion of the filament, V_F^+ is the maximum potential of the filament (V_F^+ is equal to V_F for the phase of $V_H > 0$ (see also Fig. 1(c) and (d))), S is the surface area of EP, j_p is the net current drawn by the portion of the filament, and j_{em} is the emission current. From the requirement of the floating condition of EP, $I_{EP} = 0$, the relationship between V_F^+ and V_H is adjusted by the plasma itself. Shindo et al. supposed that V_F^+ is much lower than the plasma space potential. This means that V_F^+ is out of the space-charge-limited (SCL) region. In this respect, j_{em} is independent of V_ℓ and is equal to the temperature-limited current j_{emt}. It was also assumed that j_p obeys exponential growth: $j_p \propto \exp(\Phi)$ (where $\Phi = e(V_\ell - \phi_p)/T_e$ is the normalized sheath voltage with respect to the plasma space potential ϕ_p). Thus, the following formula of Shindo for the relationship between V_H and ΔV_F of Eq. (2) in Ref. [4] has been derived from Eq. (1) as

$$\Delta V_F = -T_e \ln \left\{ \frac{T_e}{V_H} \left[1 - \exp\left(-\frac{V_H}{T_e} \right) \right] \right\}, \tag{2}$$

where ΔV_F is $\Delta V_F = V_F^+ - V_{F0}$ (V_{F0} is the floating potential at $V_H = 0$). Measuring both V_H and ΔV_F experimentally, one can estimate T_e.

Recent theoretical and experimental works reveal the dependence of the SCL current from the target plate in plasma on the plasma parameters, such as Φ and n_e [5,8]. If n_e becomes very low (such a situation appears in the present results, as mentioned below), the SCL may significantly influence the emission current. From this point of view, we should examine the validity of Eq. (2).

In the SCL region, the emission current follows the form,

$$j_{ems} = 0.5 \frac{G(\Phi)}{1 + G(\Phi)} e n_e C_e \sqrt{-\pi\Phi}, \tag{3}$$

where $G(\Phi)$ is a factor for SCL and C_e is the sound velocity for electron plasma (see also Eq. (2) in Ref. [5]). In the temperature-limited region, the emission current is given by the Richardson–Dushman's formula. On the basis of Eq. (3), j_{em} is supposed to be written as Eq. (10) of Ref. [5]. On the other hand, j_p is given as Eqs. (5) and (9) of Ref. [5] also. Substituting these defined currents into Eq. (1), we can take account of the effects of SCL on the V_H–ΔV_F characteristic. In addition, since Eq. (9) of Ref. [5] includes the electron saturation current, which has not been considered in deriving Eq. (2), the effect of the electron saturation current on the V_H–ΔV_F characteristics is also considered.

In evaluating Eq. (1) for this case, certain values of n_e, T_e, and ϕ_p are needed. Those values can be obtained with a LP; the results are shown in Fig. 3. From Fig. 3(a) it can be seen that the values of T_e obtained with the LP for the outer region ($r = 15$ mm) are comparable with those obtained by the spectroscopic method. This indicates that the LP method gives fairly reliable results for the outer region of the plasma. Thus, in order to evaluate Eq. (1), we employ the values $n_e = 1 \times 10^{14}$ m^{-3}, $T_e = 0.18$ eV, $\phi_p = 0$ V, obtained with the LP at the outer region for $P_D = 8.7$ mTorr.

The evaluated V_H–ΔV_F characteristic for various filament temperatures, T, are shown in Fig. 2(a). It can be seen that there is no difference between the curves for $T = 1600$ and 1700 K. In these cases, the emission current is much lower than the current corrected by EP (see Fig. 2(b)), and there is no effect of the SCL on the V_H–ΔV_F characteristic. In fact, both curves are almost equal to the curve obtained with Shindo's formula of Eq. (2). As T is increased, the value of ΔV_F increases. The increase in ΔV_F is not directly related to SCL but rather to the saturation of electron current corrected by EP for $V_\ell > \phi_p$. Higher temperature leads to the increase in j_{em}, and then V_{F0} shifts to a positive value, so that V_F^+ can

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[1] Even if n_e is less than 10^{17} m^{-3} at the probes, n_e near the source region is expected to be much lager than 10^{18} m^{-3} which is sufficient for the occurrence of the three-body recombination.

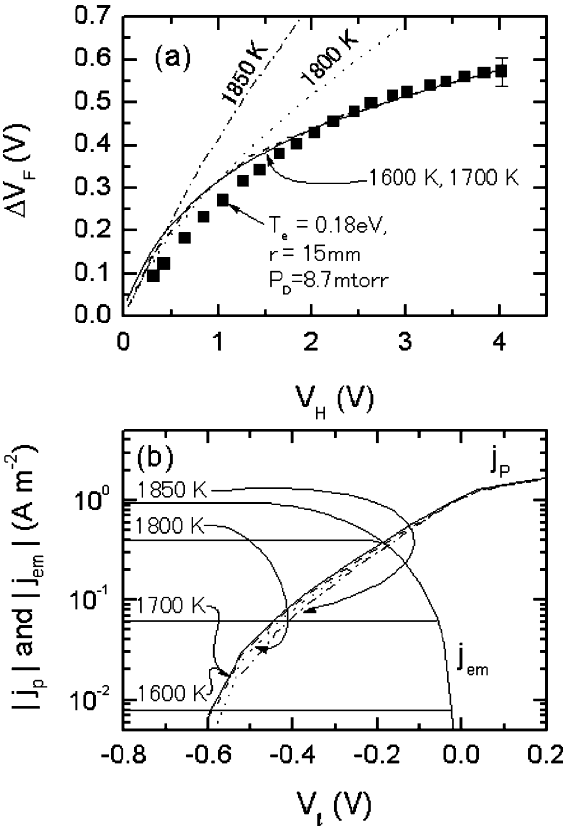

Fig. 2. Determination of T_e with the EP method. (a) Relationship between ΔV_F and V_H. Solid lines are V_H–ΔV_F characteristics evaluated by using Eq. (1) with SCL for various values of the filament temperature T. Filled squares indicate the experimentally obtained V_H–ΔV_F characteristic which gives $T_e = 0.18$ eV by using Eq. (2). (b) Evaluated current densities of j_p and j_{em} as a function of V_ℓ.

increase easily to beyond ϕ_p. When V_F^+ comes into the electron-saturation-current region, the increment of the j_p-integration of Eq. (1) for increasing V_F^+ diminishes, so that V_F^+ must rise still higher to satisfy the floating condition of $I_{EP} = 0$. Actually, if the electron saturation current is neglected ($j_p \propto \exp(\Phi)$ even for $V_\ell > \phi_p$), the difference between curves for 1800 and 1600 K almost disappears.

The V_H–ΔV_F characteristic experimentally obtained with the EP under the same condition for the LP measurement as mentioned above, which gives $T_e = 0.18$ eV by using Shindo's formula, is also plotted as the filled squares in Fig. 2(a). The experimentally obtained V_H–ΔV_F characteristic is quite similar to the theoretical curves for the cases of $T = 1600$ and 1700 K. This fact indicates that the filament temperature T in the present experiment can be determined to be less than 1700 K. If we suppose that the value of T is 1700 K and n_e is less than the substituted value of 1×10^{14} m^{-3}, ΔV_F increases as in the case of higher T. Therefore, the lower limit value of n_e ensuring the validity of Shindo's formula is 1×10^{14} m^{-3} in the present experiment.

4. Results and discussion

Fig. 3(a) shows dependence of T_e on P_D. In the inner region of the plasma, where the probes are located at the radial position $r = 0$ mm, the value of T_e obtained with EP, T_e^{EP}, is almost 2–4 eV for $P_D < 20$ mTorr. As P_D is increased to more than 20 mTorr, T_e^{EP} at the inner region decreases, reaching 0.4 eV at $P_D = 70$ mTorr. In the outer region, where the EP is located at $r = 15$ mm, T_e^{EP} ($\sim$0.2eV) is much smaller than that for the inner region.

Comparing the electron temperatures obtained by the three methods, i.e., the EP, the LP, and the spectroscopic method (using He I 2p^{3}P–nd^{3}D lines for the Boltzmann plot method [7,9]), we find the following two points: (1) A difference between T_e^{EP} and the electron temperature obtained with the LP, T_e^{LP}, appears for the inner region as P_D is increased. (2) The values of T_e obtained by the spectroscopic method fairly agree with

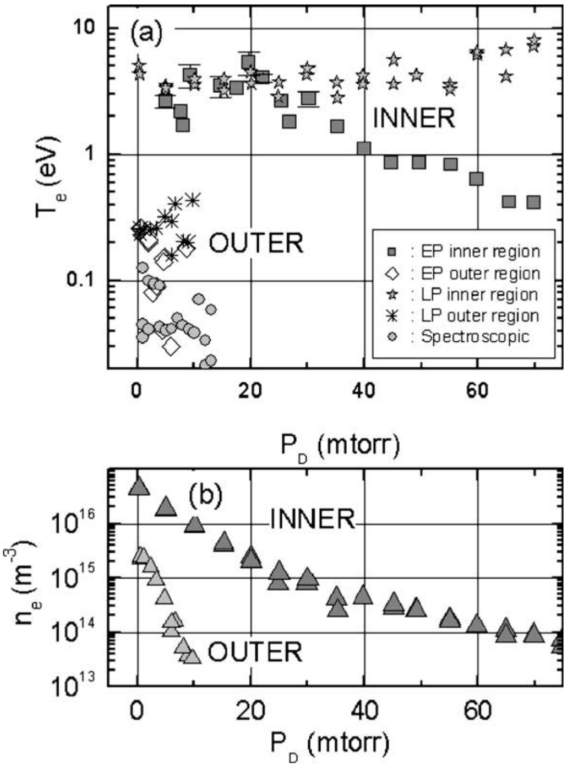

Fig. 3. Dependence of T_e and n_e on neutral pressure P_D. (a) T_e obtained with the EP, the single LP, and the spectroscopic method. (b) n_e obtained with the LP.

both T_e^{EP} and T_e^{LP} for the outer region, but are much smaller than T_e^{EP} and T_e^{LP} for the inner region.

The first point can imply that the electric resistance in the plasma affects the LP measurement [2]. Current path in the plasma can be almost neglected for the EP measurement, in comparison with the larger current path for the LP measurement. Therefore, the EP measurement gives a more reliable value of T_e than the LP measurement does.

The second point may indicate that the present spectroscopic method provides information from only the periphery of the plasma, which is consistent with the view suggested by Ohno et al. [2]. For this point, however, we would like to suggest the following: We have observed that T_e estimated by using He II 3d^{2}D–nf^{2}F lines is several times larger than that estimated by using the neutral lines, as shown above. Those ion lines are emitted mainly from the plasma column. In fact, the plasma column still remains even for the large value of P_D, as seen from Fig. 3(b). Thus, for the sake of comparing T_e values, T_e obtained by ion lines should also be employed.

5. Summary

We have used an EP to measure T_e for detached recombining plasmas in a linear divertor simulator. Considering the effects of SCL and electron saturation current on the EP measurement, we have estimated the lower limit of the electron density to ensure the validity of Shindo's formula in Ref. [4]. We have found that the EP method yielded the value of T_e more reliably than did the LP method. In addition, we have suggested that T_e obtained by detecting line emissions from ions should be employed as opposed to that obtained by either type of probe.

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