Double probe measurement in recombining plasma at NAGDIS-II

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Abstract

We have studied the validity of the double probe method in recombining plasmas. Electron temperature (T_e) measured with a double probe was quantitatively evaluated by taking into account the influences of plasma potential fluctuation, plasma resistivity, and electron density fluctuation on the current-voltage characteristic. Differential potential fluctuation and plasma resistivity between two electrodes have a minor effect on T_e especially when the inter-distance is small (typically 1 mm). Scattering of measured T_e due to the density fluctuation was sufficiently suppressed by making the data acquisition time long (typically 4 s) and taking the average. There is a good agreement between T_e measured with the optimized double probe method and that with laser Thomson scattering diagnostics.

Keywords: Double probe, Recombining plasma, Electron temperature

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I. INTRODUCTION

Detached recombining plasma is an effective method to reduce the heat flux on divertor plates in fusion devices [1–3]. Interactions between plasmas with high heat flux and neutral particles lead to cooling and steep gradient in electron temperature (T_e) along the magnetic field lines. Electron-Ion Recombination (EIR) processes, which are dominant at T_e below 1 eV, play an important role in a strong reduction in the ion particle flux to the divertor plate [4, 5]. In order to investigate the fundamental characteristics of the detached recombining plasma, accurate diagnostics of low T_e are essential because the rate coefficient of EIR processes has a strong dependence on T_e.

Electrostatic probe measurements are useful in divertor region due to their convenient setup and good spatial resolution. However, an anomaly of the current-voltage (*I*-*V*) characteristic in a single probe measurement has been identified in JET (Joint European Torus) [6, 7] and linear plasma devices, such as NAGDIS-II [8, 9] and MAP-II [10, 11]. In the recombining plasma, *I*-*V* characteristic was distorted from the conventional exponential curve and consequently showed higher T_e than other methods, e.g., optical emission spectroscopy and laser Thomson scattering (LTS) measurement. The anomaly is considered due to fluctuation of space potential and/or plasma resistivity between a probe tip and a reference electrode [9]. On the other hand, when the potential fluctuation was lower than T_e, the single probe measurement could be applicable even in the recombining plasmas without any anomaly of probe in the *I*-*V* characteristic [12, 13]. Single probe measurements are sometimes inapplicable, and sometimes applicable, and the possibility could be determined by the amplitude of potential fluctuation which depends on discharge system and condition in each device. The validity should be supported in advance by the comparison with LTS, in order to apply a single probe measurement to recombining plasma.

A double probe is a more useful method in the recombining plasma. The double probe, which has an electrically floating circuit and a short current path between two electrodes, is likely to reduce localized fluctuations near the electrodes and the effect of resistivity. However, the validity of the double probe measurement in recombining plasma has not been experimentally demonstrated.

The present study elucidates the applicability of the double probe to the recombining plasma by the experiments performed in NAGDIS-II where the anomaly of the single probe I-V characteristic is clearly observed. In order to investigate the feasibility of the T_e measurement by utilizing the double probe in the recombining plasma, it is necessary to indicate that potential fluctuation and plasma resistivity on I-V characteristic of the double probe have a minor effect on the T_e evaluation because it was already suggested that the difficulty in the single probe measurement was due to fluctuation of space potential and/or plasma resistivity. We quantitatively evaluate the influence of potential fluctuation and plasma resistivity on T_e by double probe. Further, it is also necessary to investigate the effect of density fluctuation, which is enhanced under the recombining plasma condition [14], on the double probe measurement because the density fluctuation might degrade the fitting precision in analysis of I-V characteristics. The precision of double probe measurement is discussed by taking into account the effect of density fluctuation in recombining plasma. Finally, the accuracy of T_e estimated with the double probe is demonstrated through a comparison with the LTS measurement.

II. EXPERIMENTAL SETUP

A. Plasma device

The experiments were conducted in the linear plasma device NAGDIS-II [1]. A DC arc discharge with a heated LaB_6 cathode produced helium plasma in a steady state. The length of the plasma column was ~ 2 m from the plasma source, and it was terminated with a target plate. The diameter of the plasma column was determined by the hole diameter in the intermediate electrode. The hole diameter was ~ 20 mm. In the present study, discharge current and magnetic field were set to 60 A and 0.1 T, respectively. When the additional helium gas was injected from the second gas puffing port behind the target plate, the neutral pressure (P_{n}) increased and the recombining plasma was obtained due to the enhanced plasma-neutral interactions. P_{n} was measured by using a Baratron gauge.

B. Double probe measurement

A double probe is a floating probe method developed for diagnostics in the plasma where the space potential varies temporally, e.g., high frequency plasma and decaying plasma [15, 16]. The *I*-*V* characteristic of a conventional symmetric double probe in the homogeneous plasma is expressed as

$$I_{\mathrm{p}} = I_{\mathrm{sat}} \tanh\left(\frac{V_{\mathrm{p}}}{2T_{\mathrm{e}}}\right), \tag{1}$$

where I_{p} is the probe current, I_{sat} is the ion saturation current, V_{p} is the voltage between two electrodes, and the unit of T_{e} is the electron volt. The slope of the *I*-*V* characteristic at $V_{\mathrm{p}} = 0$ gives T_{e} as follows:

$$\left.\frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}V_{\mathrm{p}}}\right|_{V_{\mathrm{p}}=0} = \frac{I_{\mathrm{sat}}}{2T_{\mathrm{ed}}}. \tag{2}$$

The double probe measurements in the present study follow the conventional theory above. In this paper, the T_e given by the double probe is represented by T_{ed}.

Figure 1(a) shows the optimized circuit for the double probe measurements. The transformer was used for making the double probe system electrically isolated from the ground potential. The turn ratio of the transformer was $N_2/N_1 = 3/1$. In the primary side of the transformer, the sine wave with the sweeping frequency (f_p) of 50 Hz was produced by the function generator (FG), and was amplified by the bipolar power supply (BPS). The output voltage of BPS was stabilized by resistors ($R_1 = R_2 = 10\ \Omega$) and a capacitor ($C_1 = 100\ \mu$F). In the secondary side of the transformer, I_p was measured from the voltage drop of the resistor (R_d) by using an A/D converter that has a large input impedance of ~ 1 MΩ with the sampling frequency of 1 MHz. The value of R_d was changed according to the plasma density from 1 to 1 kΩ.

Figure 1(b) shows a schematic of the double probe head which consists of two tungsten electrodes and an alumina rod. The length and diameter of electrodes are denoted by L and ϕ, respectively. The distance between electrodes is denoted by d. The angle between the current path and a magnetic field line is expressed by θ.

C. Laser Thomson scattering measurement

An LTS measurement system, installed on the downstream side of the NAGDIS-II [17], is able to measure T_e below 1 eV. Measured T_e by using the LTS was compared with T_{ed} measured with the double probe at the same position. The LTS measurement was conducted at $z = 1.89$ m, where z is the distance from the plasma source. The details of the LTS system in NAGDIS-II were reported in Ref. [17].

III. RESULTS AND DISCUSSION

A. Influence of differential potential fluctuation on T_e in the double probe

The potential fluctuation is enhanced under the recombining plasma condition [9]. A common mode fluctuation which does not cause difference of potential between electrodes of the floating double probe may be cancelled and not disturb *I-V* characteristics. However, the fluctuation components except for a common mode are considered to affect *I-V* characteristics. The differential potential fluctuation, caused by difference of time-variable space potential between electrodes, might change *I-V* characteristics because V_p is the voltage difference between electrodes. It is necessary to investigate the effect of differential potential fluctuation, which is defined below.

First, we define V_p and the difference of space potential between electrodes (ΔV_s) as follows:

$$V_{\mathrm{p}} = v_{\mathrm{p0}} + v_{\mathrm{p1}}, \tag{3}$$

$$\Delta V_{\mathrm{s}} = \Delta v_{\mathrm{s0}} + \Delta v_{\mathrm{s1}}, \tag{4}$$

where the subscript 0 and 1 denote the equilibrium and perturbed term, respectively. Thus I_p including fluctuation of differential potential is, from Eq. (1),

$$I_{\mathrm{p}} = I_{\mathrm{sat}} \tanh\left(\frac{v_{\mathrm{p0}}+v_{\mathrm{p1}}}{2T_{\mathrm{e}}}\right). \tag{5}$$

Even when $v_{p0} = 0$, $V_p \neq 0$ and $V_p = v_{p1}$ due to the fluctuation. By differentiating Eq. (1), the slope of *I-V* characteristic when $V_p = v_{p1}$ is given as follows:

$$\left.\frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}V_{\mathrm{p}}}\right|_{V_{\mathrm{p}}=v_{\mathrm{p1}}} = \frac{I_{\mathrm{sat}}}{2T_{\mathrm{ed}}} = \frac{I_{\mathrm{sat}}}{2T_{\mathrm{e}}} \cosh^{-2}\left(\frac{v_{\mathrm{p1}}}{2T_{\mathrm{e}}}\right). \tag{6}$$

When v_{p0} is constant and the probability density function for v_{p1} is expressed by $f(v_{p1})$, the averaged I_p is

$$\langle I_{\mathrm{p}} \rangle = \int_{-\infty}^{\infty} f(v_{\mathrm{p1}}) I_{\mathrm{p}}(v_{\mathrm{p1}}) \mathrm{d}v_{\mathrm{p1}}. \tag{7}$$

where $\langle\rangle$ denotes the average. Therefore, when the distribution function of v_{p1} is considered, T_{ed} including the effect of the potential fluctuation is

$$T_{\mathrm{ed}} = T_{\mathrm{e}} \left\{ \int_{-\infty}^{\infty} f(\Delta v_{\mathrm{s1}}) \cosh^{-2}\left(\frac{\Delta v_{\mathrm{s1}}}{2T_{\mathrm{e}}}\right) \mathrm{d}\Delta v_{\mathrm{s1}} \right\}^{-1}, \tag{8}$$

where $v_{p1} = \Delta v_{s1}$ was assumed. From Eq. (8), T_e can be evaluated by using T_{ed} and $f(\Delta v_{s1})$. Although T_{ed} is able to be measured in experiments by using the double probe, it is difficult to measure $f(\Delta v_{s1})$ directly. When we make the assumption that T_e between electrodes are the same, the difference of floating potential $\Delta V_f \sim \Delta V_s$, where V_f is the floating potential. In the present study, ΔV_f was measured instead of ΔV_s for analyzing $f(\Delta v_{s1})$.

Figure 2(a) shows $f(\Delta v_{s1})$ by using the double probe with L of 1.7 mm, ϕ of 0.5 mm, θ of 90 degrees, and d of 1 and 3 mm. The measurements were conducted with P_n = 2.0 Pa at z = 1.39 m. Although fluctuations which are observed as shown in Fig. 2(a) might have an effect on the I-V characteristics, the standard deviation denoted by σ was sufficiently small as σ = 0.08 V when d = 1 mm. Fig. 2(b) shows P_n dependence of σ. It was indicated that the double probe with small d was better for avoiding the effect of Δv_{s1}. After measuring $f(\Delta v_{s1})$, T_e can be estimated from Eq. (8). Fig. 2(c) shows the comparison between T_{ed} and T_e when d = 1 mm. It was found that effect from Δv_{s1} fluctuation was slight and did not appear on T_{ed} strongly. The contribution of the differential potential fluctuation on overestimation of T_e was ~ 3 and 6% when d = 1 and 3 mm, respectively.

When d was increased, σ was likely to increase. However, the increase in d might cause the change in plasma resistance (R_p) mentioned below. In order to observe the σ dependence of T_{ed}, d was fixed and θ was changed by rotating the probe head. Figure 3 shows θ

dependence of σ and T_{ed} by using the double probe with L of 0.7 mm, ϕ of 0.5 mm, and d of 7.5 mm when P_n = 2.4 Pa. It was indicated that σ had strong dependence on θ but T_{ed} was not affected. From those experiments, it was clearly shown that the differential potential fluctuation between electrodes due to space potential fluctuation has a minor effect on *I*-*V* characteristics of double probe in NAGDIS-II. We note that the effect of differential potential fluctuation might appear under the condition where the amplitude of the differential potential fluctuation is much larger than T_e.

B. Influence of plasma resistivity between electrodes on T_e in the double probe

In the conventional electrostatic probe analysis, we assume that R_p is much smaller than the sheath resistance (R_{sh}), which may be ignored. However, under the recombining plasma condition, the effect of R_p on single probe measurements is not negligible [9]. The large plasma resistivity in recombining plasma could not be explained by both Spitzer resistivity and plasma resistivity due to electron-neutral collision [18]. Although the length of current path in double probe is quite short, the contribution of R_p on *I*-*V* characteristics in a double probe should be quantitatively evaluated.

The theory including the effect of R_p into double probe *I*-*V* characteristics was discussed in Ref. [18]. The present study follows that theory. When the contribution of R_p is considered, effective V_p should be reduced from original V_p by the voltage drop of R_pI_p. Thus, I_p including R_p is, from Eq. (1)

$$I_p = I_{sat} \tanh\left(\frac{V_p - R_p I_p}{2T_e}\right). \quad (9)$$

By differentiating Eq. (9), the slope of *I*-*V* characteristic when V_p = 0 is given as follows:

$$\left.\frac{\mathrm{d}I_\mathrm{p}}{\mathrm{d}V_\mathrm{p}}\right|_{\substack{V_\mathrm{p}=0\\ I_\mathrm{p}=0}} = \frac{1}{R_\mathrm{p}+\frac{2T_\mathrm{e}}{I_\mathrm{sat}}}, \tag{10}$$

where the assumption that I_p = 0 when V_p = 0 in symmetric double probe was used. R_p in homogeneous plasma between electrodes could be expressed by

$$R_\mathrm{p} = \eta_\mathrm{p}\frac{d}{\phi L}, \tag{11}$$

where η_p is the plasma resistivity. Therefore, by using Eqs. (10) and (11), T_ed given as Eq. (2) could be expressed as follows:

$$T_\mathrm{ed} = \eta_\mathrm{p} J_\mathrm{sat} d + T_e = \eta_\mathrm{p}\xi + T_e. \tag{12}$$

$$\xi = J_\mathrm{sat} d, \tag{13}$$

where J_sat is ion saturation current density when the effective collection area is assumed to be $2\phi L$. From Eq. (11), T_e can be evaluated by measuring T_ed as changing d.

Figure 4(a) shows a schematic of a probe head that enables us to change d. By rotating the L-shape stainless steel (SS) tube, d can be changed while keeping ϕ and L the same. The control range of d was from 3 to 11 mm. Although θ was also changed with d in the range from 0 to 45 degrees because of the rotation of SS tube, η_p could little depend on θ as shown in Fig. 3. Fig. 4(b) shows T_ed as the function of ξ measured by using the double probe with L of 1.5 mm and ϕ of 0.5 mm. The measurements were conducted when P_n = 2.1 Pa at z = 1.72 m. In Fig. 4(b), it was found that T_ed gradually increased with ξ. This means that influence of R_p on T_ed was enhanced with increase in d, indicating that the double probe with small d was better for avoiding the effect of R_p. Further, from Eq. (12), the intercept of Fig. 4(b) gave T_e of ~ 0.39 eV. The contribution of R_p on overestimation of T_e was from ~ 3 to 16% in the range of d from 3 to 11 mm. By extrapolating T_ed, T_ed could be ~ 0.4 eV when d = 1 mm. In this case, the overestimation of T_e was ~ 1.4%.

The contributions from differential potential fluctuation and plasma resistivity to the overestimation of T_e by the double probe measurement were quantitatively evaluated. The former and latter were ~ 3–6% and 3–16%, respectively. In the case of the double probe with d of 1 mm, they were 3% and 1.4%, respectively (totaling ~ 5%). Therefore, by making d small, the double probe measurement could be possible without the critical overestimation even in the recombining plasma where the large potential fluctuation and resistivity were observed.

C. Influence of density fluctuation on T_e in the double probe

The density fluctuation is enhanced as well as potential fluctuation under the recombining plasma condition [14]. Scattering of I_p due to the density fluctuation degrades the fitting precision. Because I_{sat} is proportional to the electron density (n_e), the precision of a double probe analysis for T_e by using I_{sat} might be affected by the density fluctuation. A solution to improve the fitting precision should be taking the average of *I-V* characteristics in a steady state plasma. Although the average in time domain, a so-called moving average, changes the slope of *I-V* characteristic when V_p = 0, an ensemble average of *I-V* characteristics improves the precision of I_{sat} without any effects on the slope because of no smoothing process in time domain. In this section, in order to investigate the effect of density fluctuation on T_{ed}, the precision of a double probe is discussed by averaging *I-V* characteristics.

Figures 5(a)-(c) show the *I-V* characteristics of double probe under the plasma condition. The measurements were conducted when P_n = 3.1 Pa at z = 1.87 m by the double probe with L of 2.0 mm, ϕ of 0.5 mm, θ of 45 degrees, and d of 1 mm. In order to investigate the effectiveness of average, the measurement time was changed. When the total time for the measurement was 0.1 s, the number of *I-V* characteristics used for average was 10 because data acquisition time required for an *I-V* characteristic was 10 ms, which is determined by f_p of 50 Hz. In Figs. 5(a)-(c), the obvious improvement was observed in *I-V* characteristics when the total time for the measurement increased from 0.1 to 5 s. It was found that the ensemble average of *I-V* characteristics was effective in removing the density fluctuation even in recombining plasma.

Figure 6(a) shows the analyzed T_{ed} with changing the total time for average. The errors in T_{ed} decreased and the precision of measurements was improved with increase in the total time for average. The tendency should be due to the enhancement of fitting precision by averaging the *I-V* characteristics as shown in Figs. 5(a)-(c). When the *I-V* characteristics for 5 s were averaged, T_{ed} showed ~ 0.47 eV. Figure 6(b) shows the error ratio in T_{ed} divided by T_{ed} when the total time for average was 5 s. The horizontal dotted lines mean errors of ±5%. It was found that measurement should be taken longer than ~4 s for making the errors within ±5% in the present condition. These results indicated that the degradation of double probe measurements caused by density fluctuation could be avoided by increasing the data acquisition time and taking the average. Total measurement time for sufficiently reducing the scattering should be determined by the fluctuation level. The fluctuation level of I_{sat}, expressed as $\sigma(I_{sat})/\langle I_{sat}\rangle$, is typically ~ 0.4 in NAGDIS-II [14]. The longer measurement time than 4 s should be necessary to reduce the errors to within ±5% when the fluctuation level of I_{sat} is supposed to be larger than 0.4.

D. Comparison with the laser Thomson scattering measurements

In this section, in order to demonstrate the validity of the double probe measurement in recombining plasma, T_{ed} is compared to T_e by LTS measurements, which we define as T_{e_LTS}. For the measurements of T_{ed}, the optimized double probe method was applied, i.e. d = 1 mm and ensemble average was taken for 5 s. Figure 7(a) shows the P_n dependence of T_{ed} and T_{e_LTS} at the same position at z = 1.89 m. The measurements were conducted by the double probe with L of 1.0 mm, ϕ of 0.5 mm, θ of 45 degrees, and d of 1 mm. Fig. 7(c) also shows the comparison of T_{ed} with LTS as the function of radial position (r). The probe conditions were same as the results for P_n dependence and P_n was fixed at 1.8 Pa. As shown in Figs. 7(a) and (c), T_{ed} was in good agreement with T_{e_LTS}. The correspondence was most likely due to the optimization of measurements. It should be concluded that the double probe measurement is possible without critical overestimation or errors in T_e under the recombining plasma condition in NAGDIS-II. For the further modification, an absolutely floating and non-inductive circuit is necessary. The phase shift between I_p and V_p caused by the inductor in the transformer might change the slope in I-V characteristics to lead higher T_e. The impact is negligible in terms of f_p (50 Hz). However, burst signals during intermittent plasma structures with high frequency of > 1 kHz [19] might cause the phase shift.

Figs. 7(b) and (d) show the P_n dependence and radial profile of n_e measured by the double probe and LTS measurements. For the analysis of n_e, the probe surface area was a geometrical projection along the magnetic field lines by assuming a magnetized plasma. Although n_e was also in good agreement with LTS, quantitative comparison requires a careful estimation of the effective collection area of the electrodes.

The tendency that T_{ed} and T_{e_LTS} slightly increased at P_n > 2.2 Pa was observed in fig. 7(a). The recent study of spectroscopy and LTS in NAGDIS-II showed that two different temperature components could independently appear in time [20, 21]. The slight increase in T_e might indicate that high temperature component was dominant when P_n >2.2 Pa. The tendency was caused because the diagnostics obtained time-averaged plasma parameters. In order to separate the two temperature components, the measurements with high time resolution and/or conditional averaging technique for detecting intermittent events are required.

IV. CONCLUSION

Influences of potential fluctuation, plasma resistivity, and density fluctuation on T_e by double probe were quantitatively evaluated in NAGDIS-II. Potential fluctuation and plasma resistivity on the double probe current-voltage (*I-V*) characteristics have a minor effect on T_e evaluation. These contributions to an overestimation of T_e could be slight by making the distance between electrodes small. When the inter-distance of electrodes was 1 mm, the ~5% overestimation in T_e appeared in double probe methods. Further, the precision of double probe measurement was investigated by taking into account the effect of density fluctuation. Errors by density fluctuation were sufficiently small by taking the average when the data acquisition time was long. Measurement time should be longer than ~4 s to reduce the errors to within ±5% in the present condition. Finally, the accuracy of double probe was confirmed through a comparison with the laser Thomson scattering (LTS) measurement in terms of neutral pressure dependence and radial profile. T_e by the double probe corresponds to T_e by LTS measurement. The double probe measurement is possible without critical overestimation or errors in T_e under the recombining plasma condition.

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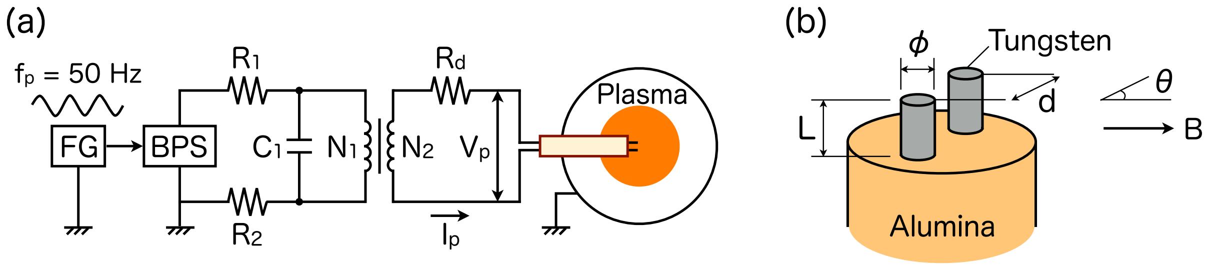

FIG. 1: (color online) (a) Electric circuit for double probe measurements in NAGDIS-II. (b) Probe head designed for double probe measurements.

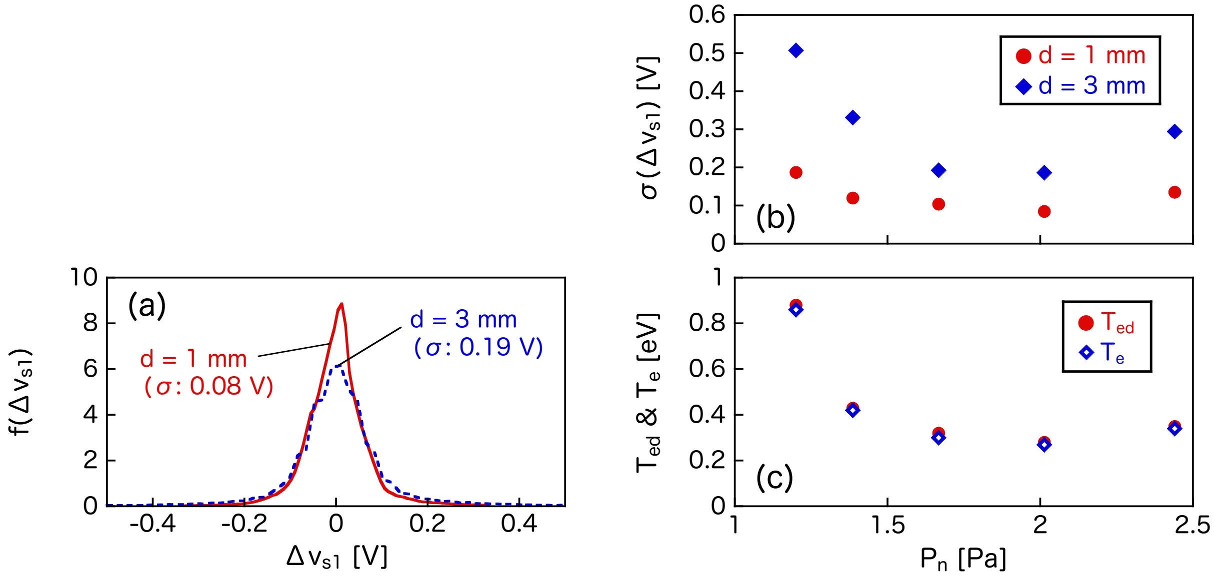

FIG. 2: (color online) (a) $f(\Delta v_{s1})$ measured by the double probe with following condition: L = 1.7 mm, ϕ = 0.5 mm, θ = 90 degrees, d = 1 and 3 mm, P_n = 2.0 Pa, and z = 1.39 m. The P_n dependence of (b) standard deviation σ of Δv_{s1} and (c) T_{ed} and T_e evaluated by Eq. (6) when d = 1 mm.

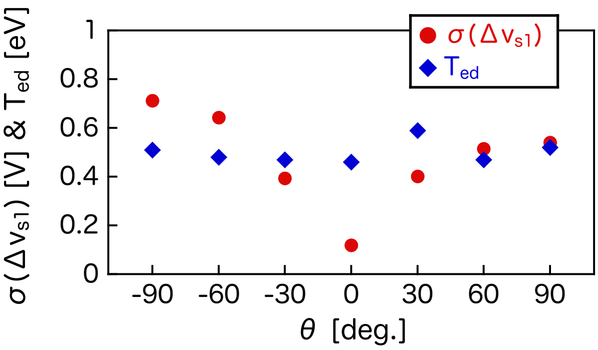

FIG. 3: (color online) θ dependence of σ (Δv_{s1}) and T_{ed} by using the double probe with following condition: L = 0.7 mm, ϕ = 0.5 mm, d = 7.5 mm, P_n = 2.4 Pa, and z = 1.39 m.

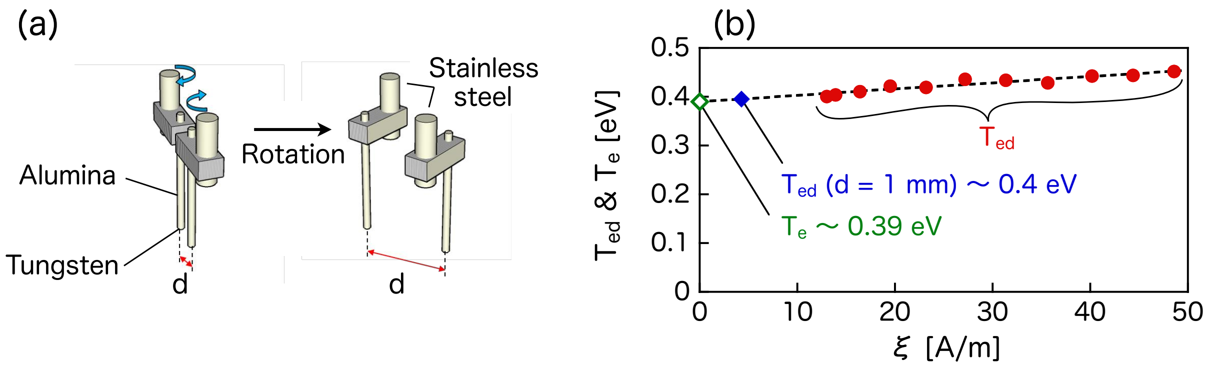

FIG. 4: (color online) (a) The probe head for changing d and (b) $T_{\rm ed}$ as the function of ξ in Eq. (13) measured by using the double probe with following condition: L of 1.5 mm, ϕ of 0.5 mm, $P_{\rm n}$ = 2.1 Pa, and z = 1.72 m.

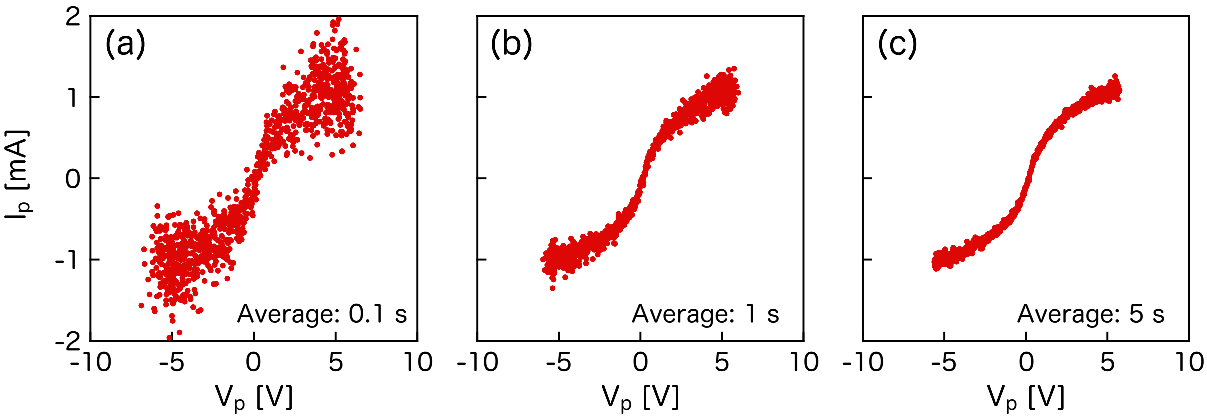

FIG. 5: (color online) Double probe *I*-*V* characteristics when the total time for averaging was (a) 0.1, (b) 1, and (c) 5 s under the following condition: L of 2.0 mm, ϕ of 0.5 mm, θ of 45 degrees and d of 1 mm, $P_n = 3.1$ Pa, and $z = 1.87$ m.

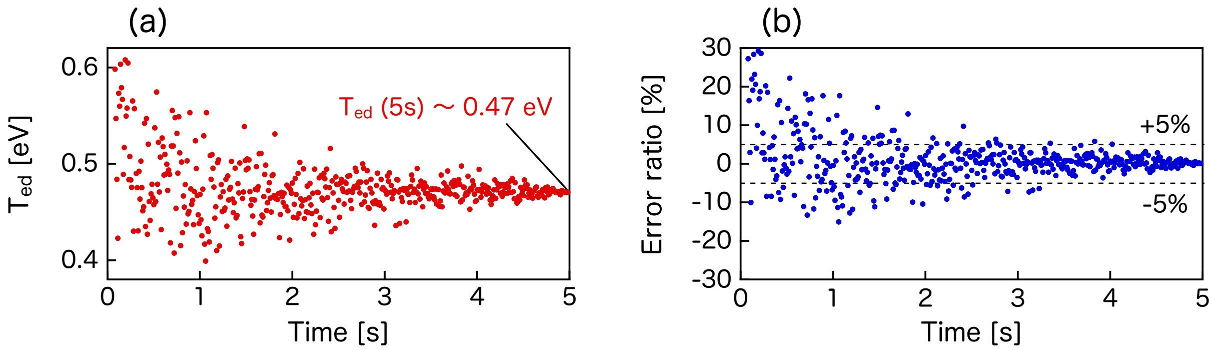

FIG. 6: (color online) (a) T_{ed} and (b) error ratio as the function of total time for average. Error ratio was defined as follows: (T_{ed} – T_{ed} (5s)) / T_{ed} (5s).

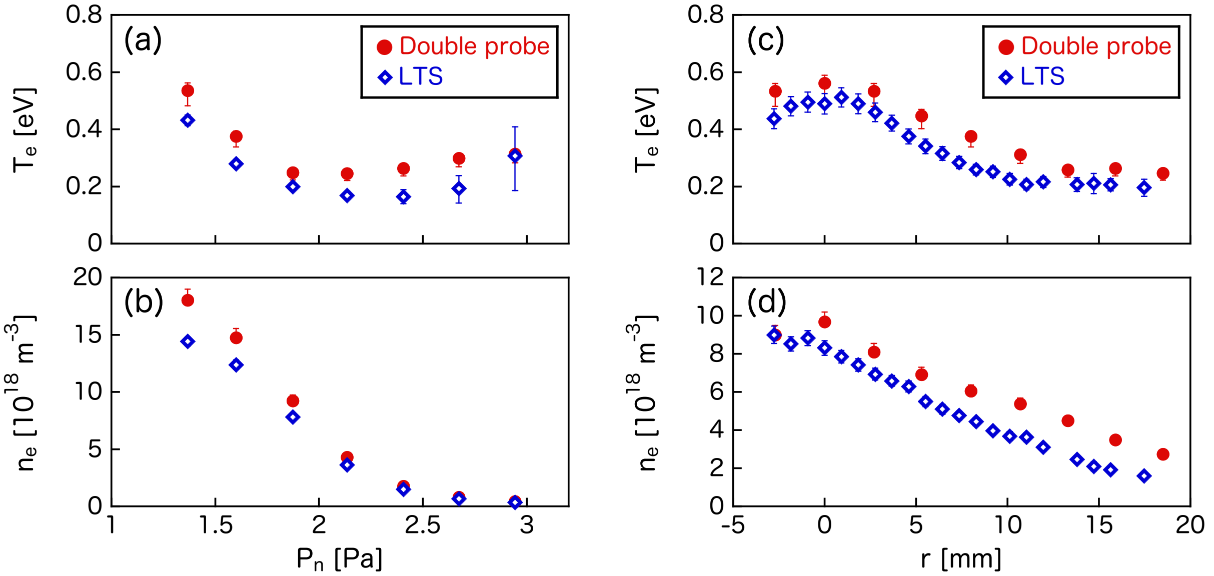

FIG. 7: (color online) T_e and n_e measured by using the optimized double probe and LTS as the function of P_n and r under the following condition: L of 1.0 mm, ϕ of 0.5 mm, θ of 45 degrees, d of 1 mm, and z = 1.89 m. An error bar in LTS measurement represents the fitting error. An error bar of +5% and -10% in T_{ed} represents the overestimation of 5% due to the differential potential fluctuation and plasma resistivity and precision of ±5% determined by density fluctuation.