Double-probe measurement in recombining plasma using NAGDIS-II

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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 characteristics. 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, electron temperature, recombining plasma

1 | INTRODUCTION

Detached recombining plasma is an effective method to reduce the heat flux on divertor plates in fusion devices.\cite{1-3} Interactions between plasmas with high heat flux and neutral particles lead to a 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.\cite{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 the divertor region due to their convenient setup and good spatial resolution. However, an anomaly of the current–voltage ($I$–$V$) characteristics in a single-probe measurement has been identified in Joint European Torus (JET)\cite{6,7} and linear plasma devices, such as NAGDIS-II\cite{8,9} and MAP-II.\cite{10,11} In the recombining plasma, $I$–$V$ characteristics were 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.\cite{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 the probe in the $I$–$V$ characteristics.\cite{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 the 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 using NAGDIS-II where the anomaly of the single-probe I-V characteristics 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 characteristics 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 $T_e$ using a double probe. Furthermore, it is also necessary to investigate the effect of density fluctuation on recombining plasma conditions,\cite{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 on recombining plasma. Finally, the accuracy of $T_e$ estimated with the double probe is demonstrated through a comparison with the LTS measurement.

2 | EXPERIMENTAL SETUP

2.1 | Plasma device

The experiments were conducted using the linear plasma device NAGDIS-II.\cite{11} A DC arc discharge with a heated LaB$_6$ cathode produced helium plasma in a steady state. The length of the plasma column was $\sim$ 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 $\sim$ 20 mm. In the present study, discharge current and magnetic fields 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 using a Baratron gauge.

2.2 | 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.\cite{15,16} The I-V characteristics of a conventional symmetric double probe in the homogeneous plasma are expressed as

$$I_p = I_{sat} \tanh \left( \frac{V_p}{2T_e} \right), \quad (1)$$

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 characteristics at $V_p = 0$ gives $T_e$ as follows:

$$\frac{dI_p}{dV_p} \bigg|_{V_p=0} = \frac{I_{sat}}{2T_{ed}}. \quad (2)$$

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

Figure 1a 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 $\sim$ 1 M$\Omega$ with a sampling frequency of 1 MHz. The value of $R_d$ was changed according to the plasma density from 1 to 1 k$\Omega$. 

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**FIGURE 1**  (a) Electric circuit for double-probe measurements using NAGDIS-II. (b) Probe head designed for double-probe measurements.

- **FG**: Function generator
- **BPS**: Bipolar power supply
- **R**: Resistors
- **C**: Capacitor
- **N**: Transformer
- **V**: Voltage
- **I**: Current
- **B**: Boundary
- **Alumina**: Material
- **Tungsten**: Material
- **$f_p$**: Sweeping frequency
- **$T_e$**: Electron temperature
Influence of differential potential fluctuation on LTS measurement

RESULTS AND DISCUSSION

2.3 | LTS 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].

3 | RESULTS AND DISCUSSION

3.1 | 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 that does not cause a difference in the potential between electrodes of the floating double probe may be cancelled and it does 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 ($\Delta V_s$) as follows:

$$V_p = v_{p0} + v_{p1}, \quad (3)$$

$$\Delta V_s = \Delta v_{s0} + \Delta v_{s1}, \quad (4)$$

where the subscripts 0 and 1 denote the equilibrium and perturbed term, respectively. Thus, $I_p$ including fluctuation of differential potential is given from Equation (1) as,

$$I_p = I_{sat \text{ tanh}} \left( \frac{v_{p0} + v_{p1}}{2T_e} \right). \quad (5)$$

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

$$\left. \frac{dI_p}{dV_p} \right|_{V_p = v_{p1}} = \frac{I_{sat}}{2T_{ed}} = \frac{I_{sat}}{2T_e} \cosh^{-2} \left( \frac{v_{p1}}{2T_e} \right), \quad (6)$$

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

$$\langle I_p \rangle = \int_{-\infty}^{\infty} f(v_{p1}) I_p(v_{p1}) dv_{p1}. \quad (7)$$

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

$$T_{ed} = T_e \left\{ \int_{-\infty}^{\infty} f(\Delta v_{s1}) \cosh^{-2} \left( \frac{\Delta v_{s1}}{2T_e} \right) d\Delta v_{s1} \right\}^{-1}. \quad (8)$$

where $\Delta v_{s1} = \Delta v_{s1}$ was assumed. From Equation (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, $\Delta V_f$ was measured instead of $\Delta V_s$ for analysing $f(\Delta v_{s1})$.

Figure 2a shows $f(\Delta v_{s1})$ by using the double probe with $L$ of 1.7 mm, $\varphi$ of 0.5 mm, $\theta$ of 90°, and $d$ of 1 and 3 mm. The measurements were conducted with $P_n = 2.0$ Pa at $z = 1.39$ m. Although fluctuations that are observed as shown in Figure 2a might have an effect on the $I$-$V$ characteristics, the SD denoted by $\sigma$ was sufficiently small as $\sigma = 0.08$ V when $d = 1$ mm.

Figure 2b shows $P_n$ dependence of $\sigma$. It was indicated that the double probe with small $d$ was better for avoiding the effect of $\Delta v_{s1}$. After measuring $f(\Delta v_{s1})$, $T_e$ can be estimated from Equation (8). Figure 2c shows the comparison between $T_{ed}$ and $T_e$ when $d = 1$ mm. It was found that effect from $\Delta v_{s1}$ fluctuation was slight and did not appear on $T_{ed}$ strongly. The contribution of the differential potential fluctuation to overestimation of $T_e$ was ~3 and 6% when $d = 1$ and 3 mm, respectively.
When \( d \) was increased, \( \sigma \) was likely to increase. However, the increase in \( d \) might cause a change in plasma resistance (\( R_p \)) mentioned below. In order to observe the \( \sigma \) dependence of \( T_{ed} \), \( d \) was fixed and \( \theta \) was changed by rotating the probe head. Figure 3 shows \( \theta \) dependence of \( \sigma \) and \( T_{ed} \) by using the double probe with \( L \) of 0.7 mm, \( \varphi \) of 0.5 mm, and \( d \) of 7.5 mm when \( P_n = 2.4 \) Pa. It was indicated that \( \sigma \) had a strong dependence on \( \theta \) 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 the 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 \( T_e \).

3.2 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 the current path in the double probe is quite short, the contribution of \( R_p \) to \( I-V \) 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 \( R_p I_p \). Thus, \( I_p \) including \( R_p \) is given from Equation (1) as

\[
I_p = I_{sat} \tanh \left( \frac{V_p - R_p I_p}{2T_e} \right) .
\]

By differentiating Equation (9), the slope of \( I-V \) characteristics when \( V_p = 0 \) is given as follows:

\[
\frac{dI_p}{dV_p} \bigg|_{V_p=0} = \frac{1}{R_p + \frac{2T_e}{I_{sat}}} .
\]
Influence of density fluctuation on

...were conducted when... where 

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...10 ms, which is determined by...

...improves the precision of... average, the measurement time was changed. When the total time for the measurement was 0.1 s, ...

...improves the precision of... a so-called moving average, changes the slope of...

...The density fluctuation is enhanced as well as potential fluctuation under the recombining plasma conditions.

...rotating the L-shape stainless steel (SS) tube, d can be changed while keeping \( \varphi \) and L the same. The control range of d was from 3 to 11 mm. Although \( \theta \) was also changed with d in the range from 0 to 45\(^{\circ}\) because of the rotation of SS tube, \( \eta_p \) could little depend on \( \theta \) as shown in Figure 3. Figure 4b shows \( T_{ed} \) as a function of \( \xi \) measured by using the double probe with L of 1.5 mm and \( \varphi \) of 0.5 mm. The measurements were conducted when \( P_e = 2.1 \) Pa at \( z = 1.72 \) m. In Figure 4b, it was found that \( T_{ed} \) gradually increased with \( \xi \). 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 \( R_p \). Furthermore, from Equation (12), the intercept of Figure 4b gave \( T_e \) of \( \sim 0.39 \) eV. The contribution of \( R_p \) to overestimation of \( T_e \) was from \( \sim 3 \) to 16\(\%\) in the range of d from 3 to 11 mm. By extrapolating \( T_{ed} \), \( T_{ed} \) could be \( \sim 0.4 \) eV when d = 1 mm. In this case, the overestimation of \( T_e \) was \( \sim 1.4\% \).

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 \( \sim 3-6 \) and 3–16\(\%\), respectively. In the case of the double probe with d of 1 mm, they were 3 and 1.4\(\%\), respectively (totalling \( \sim 5\%\)). 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.

3.3 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 conditions. 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 \( I-V \) characteristics 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 the 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 the \( I-V \) characteristics.

Figure 5a–c shows the \( I-V \) characteristics of double probe under the plasma conditions. The measurements were conducted when \( P_e = 3.1 \) Pa at \( z = 1.87 \) m by the double probe with L of 2.0 mm, \( \varphi \) of 0.5 mm, \( \theta \) of 45\(^{\circ}\), 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 Figure 5a–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 6a shows the analysed $T_{ed}$ with changing the total time for average. The errors in $T_{ed}$ decreased and the precision of measurements was improved with an 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 Figure 5a–c. When the I-V characteristics for 5 s were averaged, $T_{ed}$ showed $\sim 0.47$ eV. Figure 6b 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 $\sim 4$ s from making the errors within ±5% under 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 $\sim 0.4$ in NAGDIS-II. A longer measurement time than 4 s is necessary to reduce the errors to within ±5% when the fluctuation level of $I_{sat}$ is supposed to be larger than 0.4.

3.4 | Comparison with the LTS 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 7a shows the $P_n$ dependence of $T_{ed}$ and $T_{e,LTS}$ at the same position of plasma center at $z = 1.89$ m. The measurements were conducted by the double probe with $L$ of 1.0 mm, $\varphi$ of 0.5 mm, $\theta$ of 45°, and $d$ of 1 mm. Figure 7c also shows the comparison of $T_{ed}$ with LTS as a function of radial position ($r$). The probe conditions were the same as the results for $P_n$ dependence and $P_n$ was fixed at 1.8 Pa. As shown in Figure 7a,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 conditions in NAGDIS-II. For 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 a high frequency of $>1$ kHz might cause the phase shift.

Figure 7b,d shows 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
FIGURE 7  

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 Figure 7a. The recent spectroscopic and LTS study using NAGDIS-II showed that two different temperature components could independently appear in time.$^{[20,21]}$ The slight increase in $T_e$ might indicate that the high temperature component was dominant when $P_n > 2.2$ Pa. This tendency was caused because the diagnostics resulted in 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.

4 | CONCLUSION

Influences of potential fluctuation, plasma resistivity, and density fluctuation on $T_e$ by a double probe were quantitatively evaluated using 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. Furthermore, 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% under the present conditions. Finally, the accuracy of the double probe was confirmed through a comparison with the LTS measurement in terms of neutral pressure dependence and radial profile. $T_e$ obtained using the double probe is in agreement with $T_e$ obtained using LTS measurement. The double-probe measurement is possible without critical overestimation or errors in $T_e$ under the recombining plasma conditions.

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