Evaluation of Electron Temperature and Density Using Ion Sensitive Probes on Open Field Plasma in the End-Region of GAMMA 10/PDX*)

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Ion sensitive probe (ISP) enables simultaneous measurement of ion temperature, electron temperature, and density. So far, we have observed a difference between electron temperature, and density data obtained using ISP and Langmuir probe (LP) in divertor experimental module of GAMMA 10/PDX. To clarify the difference observed, in this study comparisons of two kinds of ISPs are performed. In Type-I ISP, in which guard electrode is aligned with outer dielectric tube, shows an influence of temperature anisotropy on the electron temperature measurement. The electron density detected using Type-I ISP is considerably smaller than the one detected using LP. In the case of Type-II ISP, in which the guard electrode protrudes from the outer dielectric tube, the electron temperature and density detected are similar to the data obtained using LP. Furthermore, the discovered effects of hydrogen (H_2) gas pressure change are presented here.

Keywords: ion sensitive probe, electron temperature measurement, electron density measurement, GAMMA 10/PDX, divergent magnetic field

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1. Introduction

Ion sensitive probes (ISPs) have been used for simultaneous measurements of ion and electron temperatures in various plasma devices. Radial ion and electron temperature profile measurements using ISPs have been performed in linear plasma devices such as PSI-2 and NAGDIS-II [1, 2]. Additionally, use of ISPs has been reported for scrape-off-layer profile measurements of the ion temperature in the Alcator C-Mod tokamak [3]. Particular to the use of ISP in helical plasma devices, ion and electron temperatures have been measured in the LHD divertor legs using an ISP [4].

An ISP consists of two electrodes, a guard electrode and an ion collector. The ion collector is recessed to the guard electrode. Depth corresponds nearly to 10 times of the electron Larmor radius. By Larmor radii difference between ions and electrons, only ions can reach the ion collector electrode, thus, the ion temperature is measured by analyzing the $I-V$ characteristics of the ion collector [5]. Additionally, high spatial resolution of ISPs makes them suitable for simultaneously obtaining detailed spatial profiles of parameters such as electron temperature, density, and spatial potential.

In GAMMA 10/PDX, ion temperature measurements using ISPs have been conducted with the inlet of the divertor simulation experimental module (D-module) placed at the end region, on open field structure, to investigate detached plasma characteristics. Under such configuration, we observed a difference between the electron temperature and density data obtained using ISP and conventional Langmuir probes (LPs) in the D-module. In this paper, we focus on the electron temperature and density measurements using the guard electrode of the ISPs on open field structure of GAMMA 10/PDX. The results are compared with data obtained using LPs.

2. Experimental Setup

2.1 Ion Sensitive Probe (ISP)

Two types of ISPs, Type I and Type II were used in this study. The present measurements and their configurations are shown in Figs. 1 (a) and (b). For Type I, the guard electrode and the outer dielectric tube were placed at the same height. Conversely, the guard electrode was protruded from the outer dielectric tube in the Type II con-

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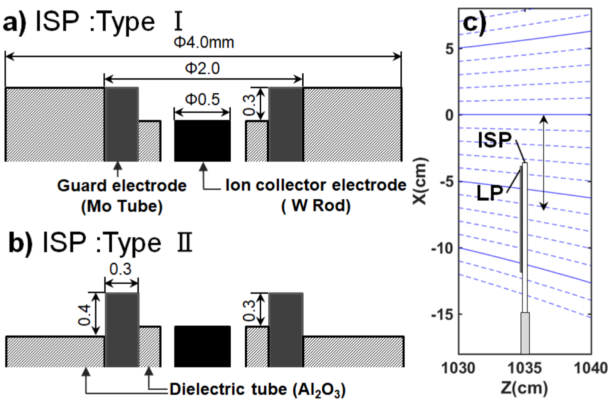

Fig. 1 (a) Type-I ISP head structure: guard electrode was aligned with the outer dielectric tube. (b) Type-II ISP head structure: guard electrode protruded 0.4 mm from the outer dielectric tube. (c) Magnetic field lines in X- and Z-directions around the ISP measurement position, at the inlet of the D-module of GAMMA 10/PDX.

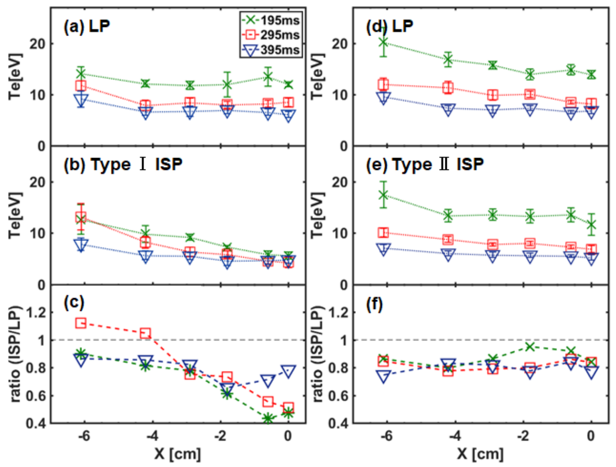

Fig. 2 X profile of the electron temperature using (a) LP and (b) Type-I ISP guard electrode. (c) Ratio of electron temperatures measured using Type-I ISP and LP. (d), (e), and (f) show the results of Type-II ISP and LP.

figuration. In the case of Type II, magnetic field line is directly connected to the guard electrode.

Electron temperature and density measurements were performed using Type-I and -II ISPs and an LP at different X positions from 0 to −6.1 cm (Fig. 1 (c)). Also, H_2 gas pressure was changed.

2.2 GAMMA 10/PDX

GAMMA 10/PDX is a large tandem mirror plasma device. End loss plasma from the west plug cell injects into the D-module installed in the west end cell [6]. ISP and LP measurements were performed at the inlet of the D-module to simultaneously measure electron temperature, density and space potential. Figure 1 (c) shows the magnetic field structure around the probes placed at the inlet of the D-module and the axis labeled Z represents the distance from the central cell center. The inlet probe position in the X-direction was changed from 0 to −6.1 cm. The magnetic field here is divergent with a gradient of approximately 0° to 8° in the radial direction and the magnetic flux density $B \simeq 1.1$ T.

3. Experimental Results

3.1 Electron temperature measurement

Figures 2 (a) and (b) show the X profile of the electron temperature measured using LP and the Type-I ISP guard electrode, respectively. Figure 2 (c) is the ratio of the temperature data obtained with ISP and LP. Figures 2 (d), (e), and (f) display results of LP and Type-II ISP. Each plot shows X profiles obtained at three different times during the discharge. Here, the gas pressure in the D-module increased with time.

The electron temperature obtained using LP is almost constant in the X-direction (Fig. 2 (a)). However, in the case of Type-I ISP, the temperature is higher at the edge region than at the center region (Fig. 2 (b)). The ratio is about 0.6 at the center ($X = 0$ cm), whereas, at the edge ($X = -6.1$ cm), the ratio is nearly one (Fig. 2 (c)). The difference between the results from Type-I ISP and LP increase toward the center. The impact of the ratio on the gas pressure is not strong.

There is no significant difference between Type-II ISP and LP results. The ratio is constantly about 0.8, regardless of the X position, and this did not change even if the H_2 gas pressure increased.

3.2 Electron density measurement

Figure 3 shows the X profile of the electron density measured with the electron temperature shown in Fig. 2. Since the dielectric tube of the ISP is located just behind the LP as shown in Fig. 1 (c), the front side of the projected area of the LP is used as the collection area for density evaluation of the LP. The result of the LP is almost constant at $X = 0$ - -4.2 cm and decreases significantly at $X = -6.1$ cm. Conversely, results from Type-I ISP slightly rises at $X = 0$ - -1.8 cm and decreases at $X = -1.8$ - -6.1 cm. Regardless of the position, the area of the upper surface of the guard electrode is used in the evaluation. The density obtained by the Type-I ISP is very small with respect to the LP (ratio = 0.06 - 0.2). The density ratio also has a dependence on the X-direction. As the probes' position moves closer to the center, results of the Type-I guard electrode deviates from results of the LP.

In the case of Type II, although the results are very similar to the LP data, the ratio at the edge regions became larger than at the center region. The ratio is within 1 ± 0.2 (Fig. 3 (f)). As the H_2 gas pressure rises, the ratio increases in all positions. Note that regardless of the measurement position, the projected area of the guard electrode protrud-

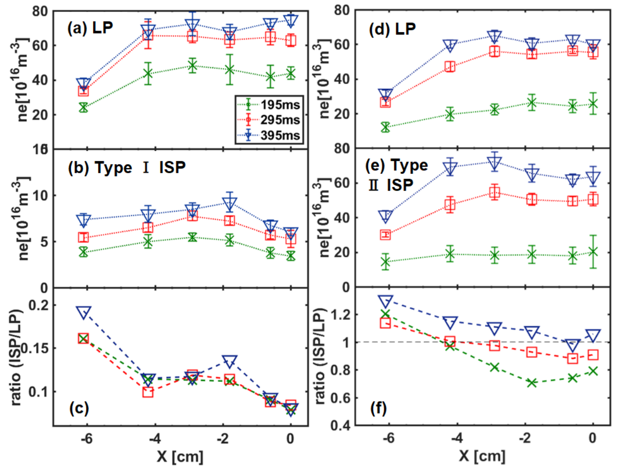

Fig. 3 X profile of the electron density measured by (a) LP and (b) Type-I ISP guard electrode. (c) Ratio of electron density measured using Type-I ISP and LP. (d), (e), and (f) show results of Type-II ISP, and LP, comparatively.

ing from the dielectric tube is used as a collection area for the density.

Using Type II instead of Type I, the X-direction dependency of the electron temperature disappeared, and the electron density evaluation was improved. However, the electron temperature detected using the Type-II ISP is slightly lower than LP, and the difference of densities still indicates an X-direction dependency.

4. Discussion

4.1 Temperature anisotropy

As shown in Figs. 2 (b) and (c), electron temperatures measured using Type-I ISP show low values at the center region. One of the reasons for such results is the temperature anisotropy. Since the measurement position is at the outside of the mirror throat, the parallel component of the velocity is larger than the perpendicular one. The anisotropy outside the throat can be estimated by the following relation:

$$v_{\parallel}^2/v_{\perp}^2 \geq \{(B_{\max}/B) - 1\}, \tag{1}$$

where $v_{\parallel}$ is the parallel component of the velocity and $v_{\perp}$ is the perpendicular one. $B_{\max}$ is the maximum magnetic flux density, and B is the magnetic flux density of the measurement position. In our set up, $B_{\max} = 3$ T and $B = 1.1$ T, then $v_{\parallel}^2/v_{\perp}^2 \sim 1.7$.

Concerning Type I, since the guard electrode is aligned with the outer dielectric tube, the magnetic field lines do not directly enter the electrode when the magnetic field lines are not inclined. However, the magnetic field lines enter the interior of the electrode at the edge region, where it meets the divergent magnetic field. The gradient is about 0 - 8° in the radial direction, with $X = 0$ - -6.1 cm (Fig. 1 (c)). Therefore, there is a strong influence of the parallel component of temperature at the edge region on the guard electrode. Thus, the temperature at the edge shows higher than the center region when using Type-I ISP.

For Type-II ISP, since the magnetic field lines directly enter the guard electrode, the temperature evaluated from Type II reflects the parallel component even near the center. Therefore, no anisotropy is considered in this case (Fig. 2 (f)).

4.2 Effective collection areas

The X-direction dependence on the density ratio is shown in Figs. 3 (c) and (f). In the case of Type II, both X-direction dependency and H_2 gas pressure dependencies are observed (Fig. 3 (f)). One of the reasons for these dependencies is the change of collection area. In the density evaluation shown in Figs. 3 (b) and (e), fixed areas were used for both Types I and II as described in Sec. 3.2. If the collection area changes with X position and/or with H_2 gas pressure, density evaluation results are influenced accordingly. We tentatively evaluate the effective collection area A using the following relation:

$$A = \frac{4I_e}{en_e}\sqrt{\frac{\pi e m_e}{8kT_e}}, \tag{2}$$

where T_e and n_e is the electron temperature and density obtained by LP, respectively. I_e is the electron saturation current obtained using the ISP guard electrode. m_e is the electron mass. Attenuation of the electron saturation current due to the magnetic field must be considered when strictly evaluating the effective collection area because Eq. (2) is derived from the theoretical formula of the electron saturation current under a no-magnetic field. However, as we are interested in discussing the relative changes on the effective area in the radial direction, the influence of the magnetic field is neglected once rough comparisons with the probe surface suffice our purposes. The calculation results for Type I and Type II are shown in Figs. 4 (a) and (b), respectively.

For Type I, the area of the guard electrode upper surface (1.6 mm^2) was used for density evaluation. According to the evaluation using Eq. (2), A is considerably small ($A = 0.1 \sim 0.4$ mm^2) (Fig. 4 (a)). The X-direction dependency on the evaluated collection area indicates that it is not appropriate to use the constant area value of the guard upper surface. The blue solid lines in Figs. 4 (a) and (b) show the evaluation of the incident area of the magnetic field lines into the inner wall of the guard electrode due to the divergent magnetic field. As the absolute value of X increases, the incident angle of the magnetic field becomes larger (Fig. 1 (c)). The evaluation of the incident area coincides approximately with the X-direction dependency of A. Therefore, the dependency of A in the X-direction is likely to be due to the incident angle of the magnetic field.

For Type II, the area for the density evaluation is 1.6 mm^2, which is the sum of the projection area of the

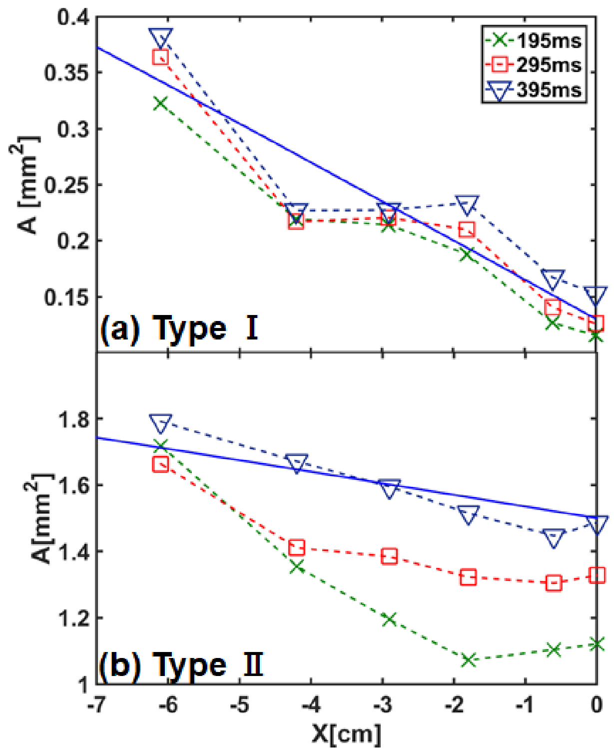

Fig. 4 Evaluation of effective collection area using Eq. (2) for (a) Type-I ISP and (b) the Type-II ISP. Blue solid lines indicate the incident area of the magnetic field lines.

front and back sides of the guard electrode. The evaluation using Eq. (2) is $A = 1 - 1.8\,\mathrm{mm}^2$ (Fig. 4 (b)). There is not much difference between the values obtained using Eq. (2). However, a dependency on the gas pressure is seen. For the highest gas pressure reached at 395 ms, A is close to $1.6\,\mathrm{mm}^2$ at the center region, but in the case of the lowest gas pressure reached at 195 ms, A is smaller than the value used for evaluation. It is conceivable that the inflow from the back side increases as the gas pressure increases. Similar to the case of Type I, X-direction dependency is also observed. The dependency is also suggested to be an influence of the divergent magnetic field.

5. Summary

Here, comparisons of measurement results obtained using two kinds of ISPs have been performed. For Type-I ISP, in which the guard electrode is aligned with the outer dielectric tube, X-direction profiles indicated that temperature anisotropy had possibly affected the electron temperature measurement. The electron density results are considerably smaller than the ones obtained using an LP. The observed low density was rationalized in terms of likely smaller effective collection area than presumed.

For Type-II ISP, in which the guard electrode protrudes from the outer dielectric tube, the electron temperature measurements yielded similar results as the ones obtained with the LP. Also, the electron density shows a similar tendency with temperature, though an impact of varying gas pressure was found. This effect might be due to the increase in inflow from the back side of the guard.

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