Electron Energy Distribution in a Divertor Simulating Device with an RF Source*)

Hiroyuki TAKAHASHI, Atsushi OKAMOTO, Takahiro KUMAGAI, Akira DAIBO, Takuya TAKAHASHI, Shimpei TSUBOTA and Sumio KITAJIMA

Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan

(Received 17 November 2013 / Accepted 20 February 2014)

Electron energy distribution measurement with oscillating plasma potential compensation was performed in the radio-frequency plasma device, DT-ALPHA. Electrons near the plasma production region are confirmed to have Maxwellian distribution. The radial profile of the electron energy distribution in the high neutral pressure region, which is maintained by secondary helium gas puffing, was also investigated. Whereas the electrons still have Maxwellian distribution, the electron temperature in the outer region of the plasma column is lower compared with the inner region. This indicates that the volumetric recombination is enhanced at the periphery of the gas target experiment in the DT-ALPHA device.

Keywords: divertor plasma, radio-frequency plasma device, volumetric recombination, helium, gas puffing

DOI: 10.1585/pfr.9.3401065

1. Introduction

A detached plasma operation is recognized as an effective method for dispersing steady heat fluxes onto plasma-facing materials such as divertor plates. Plasma detachment is achieved by enhancing volumetric recombination processes in the low electron temperature region, typically below 1 eV. However, accompanying the high-confinement mode (H-mode) transition, high energy electrons and ions are exhausted from the confinement region to the divertor region by edge localized modes (ELMs). Therefore, comprehensive understanding of the detached plasma dynamics caused by intermittent heat and particle fluxes is important for divertor plasma study. Although it is demonstrated that energetic electrons injected into detached plasma enhance ionization [1], the influence of high energy ions remains ambiguous. Moreover, energetic ions could also cause momentum transfer through the charge exchange interaction with neutral particles in the divertor region. Then, possible concerns for the ion intrinsic interactions are the redistribution of neutral particles required for the detached plasma formation.

An energy-controlled ion beam injection into a radio-frequency (RF) plasma device is a suitable method to investigate transient plasma behavior induced by ELMs. While an RF plasma source offers the advantages of penetration of beam components to the target plasma through the plasma production region and high electron density plasma production by helicon wave excitation, gas puffing into a test region is required to induce plasma-neutral interaction because the electron temperature of an RF plasma device is often several eV. Because the back-flow of secondary gas varies the discharge condition, it is difficult to sustain a stable RF discharge against a widely changing neutral pressure in the test region. In our previous work, a steady-state RF discharge coexisting with high neutral pressure environment in the test region by helium gas puffing was achieved by adopting a differential pumping system and back-flow suppressing orifices [2]. Then, a helium recombining plasma was successfully produced with large amounts of secondary gas puffing [3]. In the experiment in Ref. 3, the emission intensity from highly excited helium atoms of 2^3P–n^3D ($n \leq 14$) was observed. Here, n represents the principal quantum number. The Boltzmann plot method using light emission intensities from the Rydberg helium atoms gives an electron temperature of $T_e \sim 0.05$ eV. However, the detailed spatial distribution of the He I emission intensity was not discussed in Ref. 3. Then, the radial profile of Rydberg helium atoms was measured using relatively small amounts of gas puffing [4]. This revealed that the Rydberg helium atoms localize at the periphery of the cylindrical plasma, whereas atoms in the lower excited state have a center-peaked profile. The cross sections of the electron-ion recombination (EIR) are known to be highly dependent on the electron temperature. Hence, difference in the electron temperature toward radial direction could cause such a localization phenomenon. The Langmuir probe method is a conventional technique to obtain the electron temperature with high spatial resolution. However, because evaluation of the electron temperature from the slope of I-V characteristics is based on the Maxwellian distribution of plasma, deviations from the distribution result in electron temper-

author's e-mail: hiroyuki.takahashi@ppl2.qse.tohoku.ac.jp

*) This article is based on the presentation at the 23rd International Toki Conference (ITC23).

ature uncertainties. The electron energy probability function (EEPF), derived from the second derivative of the I-V characteristics, gives the degree of deviation from the Maxwellian distribution. Therefore, it is important to investigate EEPFs over a wide range of neutral pressure to understand the forementioned transition to the recombining plasma in the periphery. However, measurements of EEPFs in an RF plasma are usually difficult owing to the oscillating plasma potential. In this paper, the first measurements of EEPFs in the RF divertor plasma simulator DT-ALPHA are reported. Experimental setup is described in Sec. 2. Then, the experimental results are presented and discussed in Sec. 3 followed by a summary in Sec. 4.

2. Experimental Setup

2.1 RF plasma device DT-ALPHA

Experiments were performed with a linear divertor plasma simulator DT-ALPHA [5]. Figure 1 (a) shows a schematic of the DT-ALPHA device. The vacuum vessel consists of a stainless steel (SUS) chamber (63 mm inner diameter) and quartz tube (36 mm inner diameter) coupled with an RF antenna. The total length of the device is approximately 2 m, and x, y and z axes are as shown in Fig. 1 (a). Helium working gas is injected into the DT-ALPHA device near the upstream end-plate. Helicon plasma is produced by 13.56 MHz oscillating field from the RF antenna. The plasma is terminated at both end-plates. At the downstream region (z = 1.58 m), helium secondary gas, the flow rate of which is controlled with a needle valve, is injected into the DT-ALPHA device to decrease the electron temperature. Three sets of orifice units of 20 mm inner diameter are installed in the device to control spatial distribution of the neutral pressure. The neutral pressure at the test region (z = 1.43 m) is controlled from below 1 Pa to above 10 Pa without significant backflow of the secondary gas. The direction of the converging magnetic field line corresponds to the z axis, and the magnetic field strength is approximately 0.2 T at the test region. Measurements were performed with an RF compensated probe at the upstream region (z = 0.98 m) and the test region with helium gas puffing. The cross section of the test region is shown in Fig. 1 (b). Figure 2 is a schematic of the RF compensated probe described in the next section.

2.2 RF compensated probe design

In the RF plasma source, the oscillating plasma potential distorts the I-V characteristics obtained by the Langmuir probe method and overestimates the electron temperature [6]. Then, the RF compensation method with a reference electrode can be used to acquire the undistorted electron temperature or EEPF [7]. A schematic of the RF compensated probe used in this experiment is shown in Fig. 2. The molybdenum probe tip, 0.15 mm in diameter and 1 mm in length, is surrounded by a ceramic tube of 0.8 mm outer diameter. The reference electrode of the

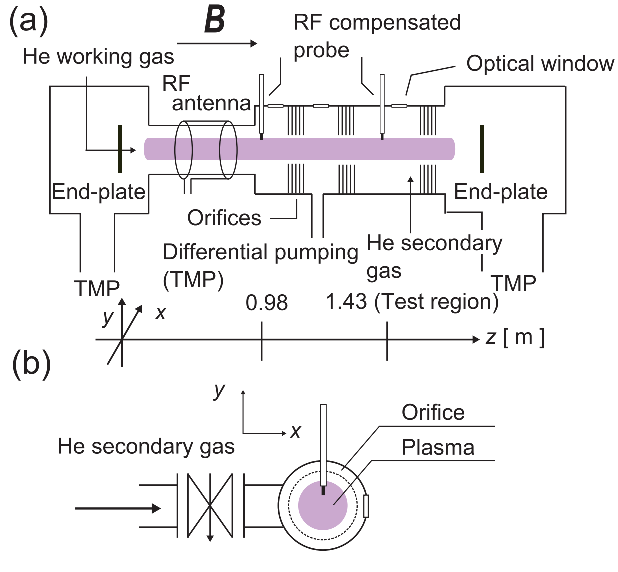

Fig. 1 Schematic of the divertor plasma simulator DT-ALPHA (a) and cross section of the test region (b).

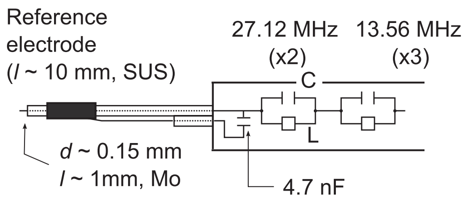

Fig. 2 Schematic of the RF compensated probe.

10 mm long SUS tube is placed to compensate the oscillating field. The distance from the probe tip to the reference electrode is approximately 3 mm. The molybdenum and reference electrodes are connected electrically via a 4.7 nF capacitor. Then, each electrode is connected to five choke coils with impedance resonances at fundamental (13.56 MHz) and second-harmonics (27.12 MHz) frequencies. EEPF g_p is described by the second derivative of the electron current as $g_p \propto d^2I_e/dV_p{}^2$. V_p represents the probe potential. In this experiment, g_p is obtained by careful numerical differentiation of I_e.

3. Experimental Results and Discussion

3.1 Plasma production region

Figure 3 shows the radial profile of the electron temperature, electron density, and space potential at z = 0.98 m measured by the RF compensated probe (squares) and non-compensated probe (circles), respectively. The electron temperature and electron density obtained by the respective probes have almost similar distributions across the plasma column. On the other hand, there are obvious differences in the space potential. In the non-compensated probe, the space potential profile is hollow, whereas its tendency is opposite when the potential oscillation is com-

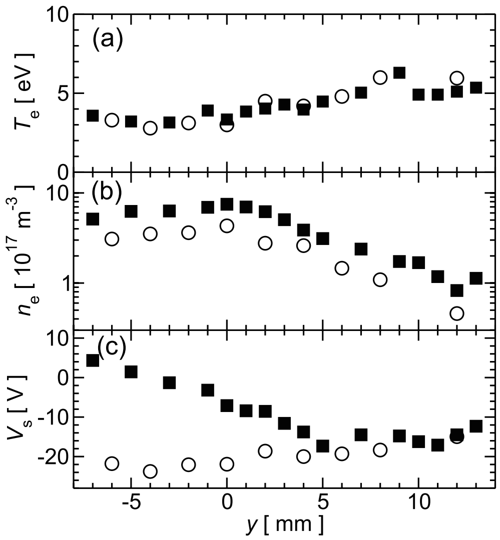

Fig. 3 Radial profiles of the electron temperature (a), electron density (b) and space potential (c) at the plasma production region of $z = 0.98$ m obtained with RF compensated probe (squares) and non-compensated probe (circles), respectively. RF power was maintained at approximately 140 W.

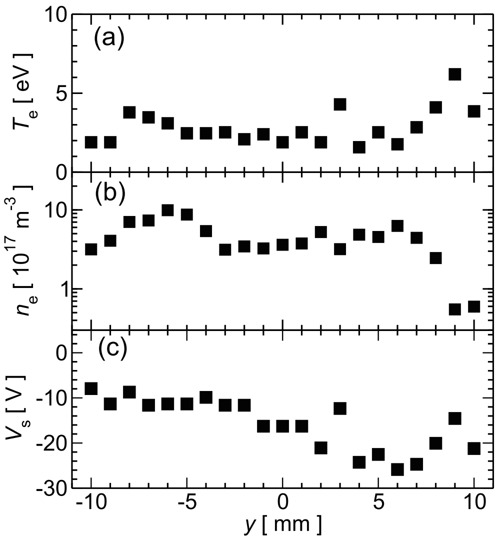

Fig. 5 Radial profiles of the electron temperature (a), electron density (b) and space potential (c) at the test region with helium gas puff. Neutral pressure is approximately $p = 5.7$ Pa.

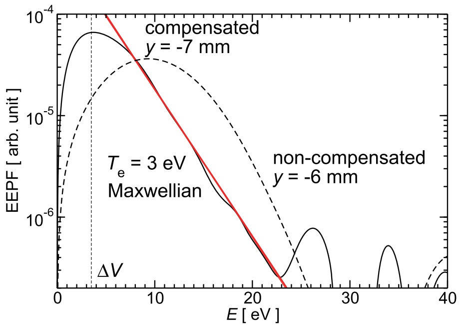

Fig. 4 Electron energy probability functions near the plasma production region obtained with RF compensated probe (solid line) and non-compensated probe (dashed line).

pensated. Compared with the core region, the difference in the space potential is smaller in the outer region because the RF compensation becomes ineffective. EEPFs obtained by the second derivative of the *I*-*V* characteristics are shown in Fig. 4. The solid line represents EEPF obtained with the RF compensated probe, and the slope is well fitted by a 3 eV Maxwellian function, which corresponds to the energy gap ΔV between the peak and the zero crossing of EEPF, namely, $\Delta V \sim T_e$. In EEPF obtained with the non-compensated probe, however, the energy gap is significantly larger than the electron temperature and rounding appears at its peak. It is confirmed that the electron temperature and electron density from the *I*-*V* characteristics obtained near the plasma production region are not significantly different although the plasma potential oscillates with fundamental and second-harmonics frequencies. However, the space potential and EEPF become ambiguous owing to the RF distortion in non-compensated measurements.

3.2 High neutral pressure region

The radial profiles of the electron temperature, electron density, and space potential were also measured at the test region with helium gas puff (Fig. 5). The neutral pressure at the test region was approximately $p = 5.7$ Pa and the RF power for plasma production was approximately 600 W. The electron temperature was approximately $T_e = 2 \sim 4$ eV inside the plasma column. The radial distribution of the electron density becomes hollow and peaks at $y = \pm 6$ mm and then rapidly decreases near the plasma boundary at $y = \pm 10$ mm, which corresponds to the inner diameter of the orifices. The high electron density plasma of $n_e \simeq 10^{18}$ m^{-3} required for the volumetric recombination is achieved in the region of $y = \pm 6$ mm although that of the plasma center decreases to $n_e \sim 4 \times 10^{17}$ m^{-3}. The space potential has similar radial distribution with the upstream region, as shown in Fig. 5 (c). Note that the space potential at the outer position is ambiguous because the RF compensation is moderate.

To discuss the enhancement of the plasma recombination at the edge region observed in the moderate neutral pressure case, the electron energy distribution is measured at two neutral pressure, $p = 5.7,\ 2.8$ Pa. Figure 6 shows EEPFs at $y = -5,\ -10$ mm, where the reference electrode is well inside the plasma. In the higher neutral pressure case of $p = 5.7$ Pa, EEPF is well fitted by a single Maxwellian function, as shown in Fig. 6 (a). In the lower pressure case of $p = 2.8$ Pa, although the slope of EEPF is slightly rounded, the electron temperature is approximately estimated by its slope. The electron temperature

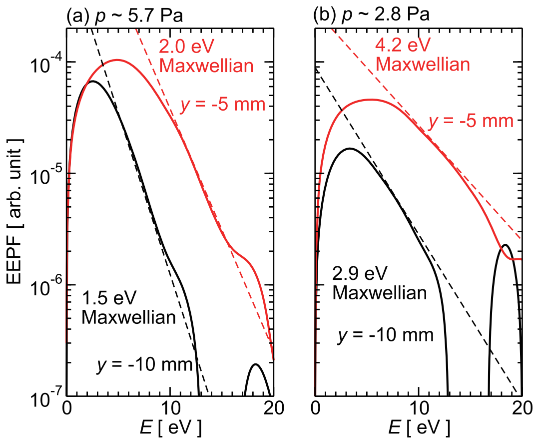

Fig. 6 Electron energy probability functions at the test region for neutral pressure $p = 5.7$ Pa (a) and $p = 2.8$ Pa (b) with moderate helium gas puffing.

decreases by increasing neutral pressure at each radial position. Moreover, these results indicate that electrons at the test region still have single Maxwellian distribution at several Pa. As shown in Fig. 6, the electron temperature near the plasma boundary is slightly smaller than that of the inner region. This is a one of the possible reasons for localization of highly excited helium atoms owing to volumetric recombination. For example, the collisional-radiative (CR) rate coefficient of recombination processes at $y = -10$ mm calculated using the helium CR model [8,9] is approximately 1.5 times larger than that of $y = -5$ mm in each neutral pressure case. The electron temperature from the slope of EEPF is used to calculate the recombination rate coefficient. However, detailed measurements of EEPFs with more widely changing neutral pressure are required to understand the enhancement of the volumetric recombination in the outer region.

4. Summary

The method to measure the electron energy distributions is improved using an RF compensated probe in the divertor plasma simulator, DT-ALPHA. Although the electron temperature and electron density are independent on the RF compensation, the space potential and electron energy probability function are strongly dependent on it. In the plasma production region, the electrons have single Maxwellian distribution. The electrons at the test region with helium gas puffing are also shown to have Maxwellian distribution. However, the electron temperature in the outer region is slightly lower than that of the core region, and the CR rate coefficient of the recombinations is larger at the outer region. Though this result qualitatively explains the localized enhancement of the recombination processes, more detailed investigation is required to understand the recombining plasma formation in the DT-ALPHA device.

Acknowledgment

The work was partly supported by JSPS KAKENHI Grant Numbers 22740357 and 24246152.

[1] N. Ohno, D. Nishijima, S. Takamura, Y. Uesugi, M. Motoyama, N. Hattori, H. Arakawa, N. Ezumi, S. Krasheninnikov, A. Pigarov and U. Wenzel, Nucl. Fusion **41**, 1055 (2001).
[2] A. Okamoto, H. Takahashi, Y. Kawamura, A. Daibo, T. Kumagai, S. Kitajima and M. Sasao, Plasma Fusion Res. **7**, 2401018 (2012).
[3] H. Takahashi, A. Okamoto, Y. Kawamura, T. Kumagai, A. Daibo and S. Kitajima, Fusion Sci. Technol. **63** 1T, 404 (2013).
[4] A. Okamoto, H. Takahashi, Y. Kawamura, T. Kumagai, A. Daibo, T. Takahashi and S. Kitajima, Proceedings of the 40th EPS Conference on Plasma Physics, Espoo, Finland, 1-5 July 2013, ECA Vol. 37D, P1.129.
[5] A. Okamoto, K. Iwazaki, T. Isono, T. Kobuchi, S. Kitajima and M. Sasao, Plasma Fusion Res. **3**, 059 (2008).
[6] I.D. Sudit and F.F. Chen, Plasma Sources Sci. Technol. **3**, 162 (1994).
[7] K. Takahashi, C. Charles, R. Boswell, M.A. Lieberman and R. Hatakeyama, J. Phys. D: Appl. Phys. **43**, 162001 (2010).
[8] M. Goto, J. Quant. Spectrosc. Radiat. Transfer **76**, 331 (2003).
[9] T. Fujimoto, J. Quant. Spectrosc. Radiat. Transfer **21**, 439 (1979).