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Plasma temperature rise toward the plasma-facing surface

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ABSTRACT

Detailed measurements of axial electron temperature, T_e, profiles in the presheath region were carried out using a Langmuir probe and the line intensity ratio technique for both He I (728.1 nm/706.5 nm) and Be II (467.3 nm/313.1 nm). The results show that T_e increases toward the material surface, which contradicts the standard picture that T_e is constant along the magnetic field in the sheath-limited regime. While no target bias voltage, V_b, dependence is seen, the T_e rise becomes more prominent with decreasing neutral pressure. Similarly, the ion temperature, T_i, evaluated from Doppler broadening of a He II line emission at 468.6 nm is found to increase toward the surface, but also does not depend on V_b. Possible mechanisms of the T_e and T_i rise as well as validity of the line intensity ratio technique near the material surface are discussed.

1. Introduction

The electron temperature, T_e, is an essential parameter for understanding both plasma-gas and plasma-material interactions. Electron-impact collision processes depend strongly on T_e [1], and play an important role in the formation of detached plasmas [2]. The photon emissivity coefficient, PEC, and the ionization events per photon, *S/XB*, are also a function of T_e [3]. These parameters are critical to obtain particle densities and sputtered impurity fluxes from line emission intensities. The sputtering yield of material is an important factor in determining the lifetime of plasma-facing components, and is a strong function of the incident ion energy [4], which is mainly determined by T_e via the sheath potential drop. The heat load onto the surface is also affected by T_e through the sheath energy transmission factor [5]. It should be noted that both the sheath potential drop and the sheath energy transmission factor are also affected by the ion temperature, T_i.

It is normally assumed that T_e is constant along the magnetic field in the presheath region toward a material surface in the sheath-limited regime [5]. On the other hand, it was reported from the PISCES-A linear device that T_e inferred from the difference between the space and floating potentials becomes higher near the material surface in a plasma containing a significant amount (~10%) of hot electrons ($T_e^h \sim 30$ eV, compared to the cold bulk $T_e^c \sim 12$ eV) [6]. It was claimed that the existence of hot electrons is essential for the effective T_e rise. In linear devices like PISCES, the hot electron component originates from primary electrons from the discharge plasma source. In the boundary plasma of tokamaks, hot electrons can also exist, and were confirmed with Langmuir probe measurements in the CASTOR tokamak [7].

In this paper, we experimentally investigate axial T_e profiles near the target in plasmas, where the hot electron component is negligibly small ($\leqslant$0.1%, if any). Both spectroscopic and Langmuir probe methods are used to measure T_e. In addition, the He^+ ion temperature, T_{He+}, and the neutral He temperature, T_{He}, are evaluated from Doppler broadening of spectral lines.

2. Experimental setup

The experiments were performed in the PISCES-B linear device [8]. In Fig. 1, the target region is schematically shown. Two spectroscopic systems were used, i.e. one for T_e and another for T_{He+} and T_{He}. The first system consists of a 0.5 m Czerny–Turner type spectrometer (Acton SP2560) equipped with a 2-D CCD camera (Princeton Instruments PIXIS:400B). Plasma light emission is directly transferred to the entrance slit of the spectrometer via a plane mirror, a Dove prism, and a focusing lens. Since the image is rotated with the Dove prism, the axial profile is collected in a single acquisition. The spatial resolution is 1.34 mm per CCD channel. This system measures axial profiles of line intensity ratios of He I (728.1 nm/706.5 nm) [9] and Be II (467.3 nm/313.1 nm) [10], which are sensitive to T_e. The line-of-sight (LOS) of this system is indicated with a dashed line in Fig. 1.

The second system is employed to measure T_{He+} and T_{He} from Doppler broadening of a He II line at 468.6 nm and He I line at

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492.2 nm, respectively. Plasma emission is delivered via an optical fiber to the entrance slit of a 1.33 m Czerny–Turner type spectrometer (McPherson 209) with a 2-D ICCD camera (Princeton Instruments). The line shape is measured in second order for better spectral resolution [9]. The dispersion of the system is 5.95×10^{-3} nm/pixel at 468.6 nm and $5.78\text{x}10^{-3}$ nm/pixel at 492.2 nm. Since the instrumental function is Lorentzian with a full width at half maximum (FWHM) of $\sim 8 \times 10^{-3}$ nm, the measured line is fitted with a Voigt function. For the He II line, 13 fine structures are taken into account for the fit. It should be noted that the FWHM of Stark broadening of the He II line at a typical electron density $n_e = 10^{19}\ \mathrm{m}^{-3}$ in our experiment presented here is calculated to be less than 2.5×10^{-4} nm [11], which is negligibly small compared to that of Doppler broadening ($\sim 1.3 \times 10^{-2}$ nm at $T_{He+} = 0.5$ eV). The LOS of this system (the diameter of the spot $\sim$10 mm) is fixed, and is the same axial location as the reciprocating single probe system. Thus, the target position, defined as $z = 0$ mm, is axially scanned to obtain axial profiles.

Fig. 2 presents examples of measured electron current (I_e)-applied probe voltage (V_p) characteristics of the single probe measured at $z = 5$ mm in He plasmas at different neutral pressures P_{He} = 8 and 2 m Torr. As can be seen, the measured data is well fitted with a single Maxwellian up to $V_p = -80$ V even at P_{He} = 2 m Torr. Calculated bi-Maxwellian curves are also shown, where the fraction of hot electrons β_h = 0.1% and 1%, and the temperature T_e^h = 30, 50, and 100 eV are assumed. β_h is defined as $n_e^h/(n_e^c + n_e^h)$ with the bulk cold electron density, n_e^c, and the hot electron density, n_e^h. From comparison with the calculated bi-Maxwellian curves, β_h is expected to be of the order of 0.1% or below, which is much smaller than that in Ref. [6].

3. Experimental results

3.1. Neutral pressure scan

The P_{He} dependence of axial T_e profiles measured with the single probe is displayed with symbols in Fig. 3(a). Each plotted point is the average of $\sim$5–10 data points collected around the center ($r \leqslant 10$ mm) of the plasma column from 3 probe shots. The radial profiles of T_e as well as n_e are nearly flat at $r \leqslant 10$ mm [12]. Error bars are the standard deviation of the mean. In this example, Be was seeded with a high-temperature effusion cell into He plasma, which was terminated with a Mo target at the floating potential. With decreasing P_{He}, the T_e rise toward the target is found to become more prominent. Since T_e is proportional to the difference between the space, V_s, and floating, V_f, potentials [5], $(V_s–V_f)/3.5$ is also shown in Fig. 3(a), the trend of which is consistent with that of T_e.

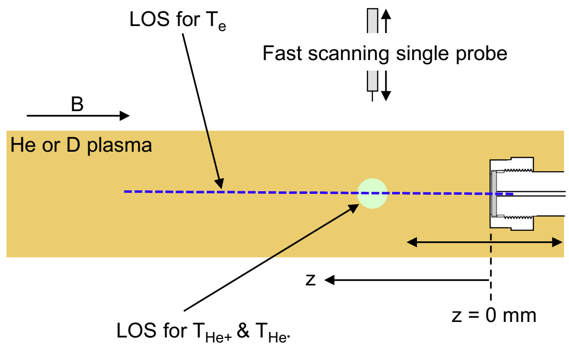

Fig. 1. Schematic view of the PISCES-B target region. The target surface is defined as $z = 0$ mm. The line-of-sight (LOS) of two spectroscopic systems is indicated. The axial position of the reciprocating probe system is the same as the LOS of the high-resolution spectroscopic system for T_{He+} and T_{He} measurements.

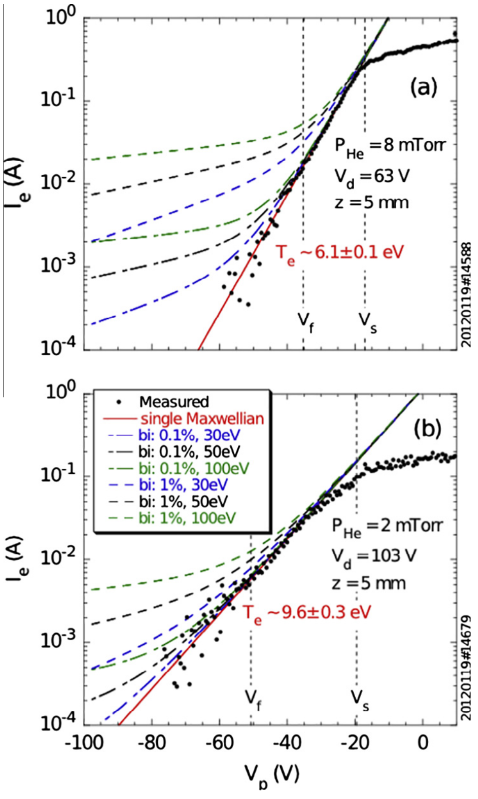

Fig. 2. Measured I_e–V_p characteristics of the single probe in He plasmas at (a) P_{He} = 8 m Torr and (b) 2 m Torr. The measured data is well fitted with a single Maxwellian. Calculated bi-Maxwellian curves (β_h = 0.1% and 1%, T_e^h = 30, 50, and 100 eV) are shown with dashed lines.

Measured line intensity ratios of both He I and Be II, presented in Fig. 3(b) and (c), also indicate the T_e rise, because the ratios increase with an increase in T_e, as shown in Fig. 3(d). The He I and Be II ratios are calculated with the Goto code [13] and the ADAS database [14], respectively. Since T_{He} was not measured, the radiation trapping effect cannot be precisely calculated [9], and T_e is not evaluated from the He I line intensity ratio here. Inferred T_e from the Be II line intensity ratio is plotted with solid lines in Fig. 3(a). The line intensity ratio technique seems to be more sensitive to T_e than the single probe, and the T_e rise is visible even at higher P_{He}.

3.2. Target bias voltage scan

In Fig. 4(a), axial T_e profiles (top), obtained with the He I line intensity ratios (bottom), are plotted as a function of the target bias voltage, V_b, which determines the incident ion energy to the target as $E_i = V_s–V_b$. In this experiment, V_s was around -4 V in the upstream, and a W sample was exposed to pure He plasma with $P_{He} \sim 5$ m Torr. It can be seen that the axial T_e profile does not depend on V_b. This is consistent with probe measurements, as shown with symbols.

Axial T_{He+} and T_{He} profiles are shown in Fig. 4(b) and (c), respectively. Since (1) the discharge power mainly goes to electrons and (2) ions can effectively transfer the energy to neutrals through charge–exchange and elastic collisions, T_{He+} is typically much lower than T_e in linear devices. Furthermore, T_{He+} is also found to increase toward the target, while the T_{He} profile is flat. Similarly to T_e, both T_{He+} and T_{He} show no V_b dependence. It is worth noting that the T_{He+} rise seems to start at $z \sim 30$ mm, while T_e starts to