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Evaluation of electron temperature in detached recombining plasmas

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Abstract

Detailed spectroscopic measurements have been carried out in the linear divertor plasma simulator, NAGDIS-II in order to acquire the accurate evaluation of the electron temperature, which leads to a deeper understanding of the characteristics of detached recombining plasmas. Electron temperature in the detached recombining plasmas was evaluated by two different spectroscopic methods, using continuum emission and a series of line emission from highly excited levels, giving different electron temperatures. The reasons are discussed based on the effects of energetic electrons.

Keywords: NAGDIS-II; Spectroscopy; Volume recombination

1. Introduction

In detached divertor regime, particle balance in the SOL and the divertor region is strongly influenced by volume recombination processes at the low electron temperature T_e. For the accurate evaluation of the particle balance, the precise measurement of T_e and the electron density n_e is crucial because the rate coefficient, $\langle \sigma v \rangle_{rec}$, of electron–ion recombination (EIR), which includes radiative and three-body recombinations, has a strong dependence for n_e and especially T_e, as $\langle \sigma v \rangle_{rec} \propto n_e T_e^{-4.5}$.

Electrical probe measurement is usually used for the evaluation of T_e. In the recombining plasmas, however, it has been shown that the probe measurement does not work at all [1,2], giving a enormously high T_e. Therefore, in the recombining divertor plasmas spectroscopic measurements would be useful [3–7]. The following spectroscopic techniques for the determination of T_e in the recombining plasmas are mainly used; (1) Relative continuum intensities method, (2) Continuum method, (3) Boltzmann plot method, etc. The method (1), using a ratio of intensities on both sides of a series limit, is not appropriate for the very low T_e (<1 eV) since the ratio of intensities diverges. The method (2), which uses a slope of continuum emission, is a more robust method for $T_e < 1$ eV. From the absolute continuum intensity, n_e can be also obtained. The method (3) is often used because a good signal to noise ratio can be obtained owing to the use of a series of line emission.

In this paper we have performed the accurate evaluation of T_e using two methods of (2) and (3) in steady state detached recombining helium plasmas of the linear divertor plasma simulator, NAGDIS-II. We discuss a difference of the T_e obtained by these two methods.

2. Experimental setup

The experiments were performed in the linear divertor plasma simulator, NAGDIS-II [8], which can

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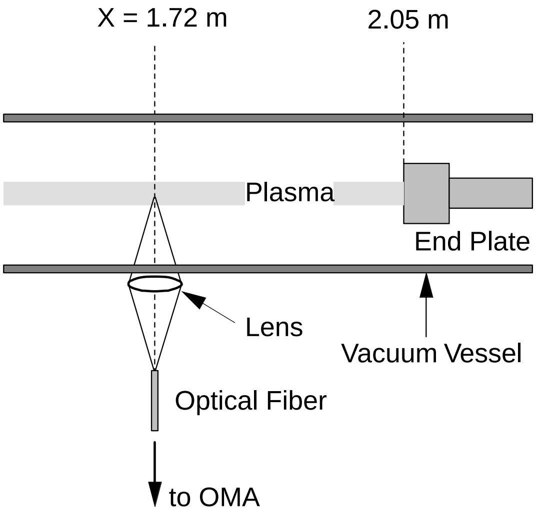

Fig. 1. Schematic view of the spectroscopic measurement in the downstream region of the linear divertor plasma simulator, NAGDIS-II.

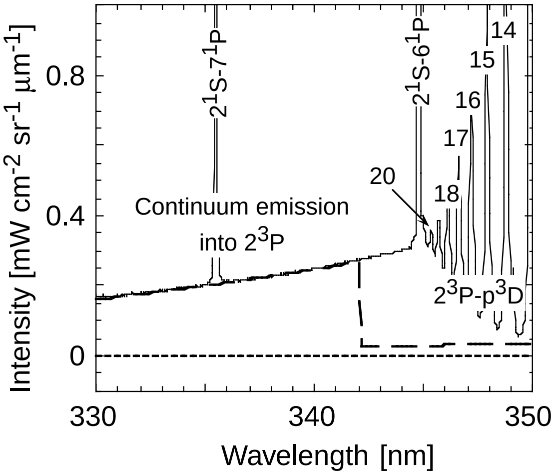

Fig. 2. Spectrum from a detached recombining helium plasma at $P_u \sim 6.1$ mTorr (solid line) and theoretically calculated continuum spectra at $T_e = 0.23$ eV, $n_e = 2.24 \times 10^{19}$ m^{-3} (long-dashed line) and $T_e = 50$ eV, $n_e = 2.24 \times 10^{17}$m^{-3} (short-dashed line).

operate in steady state by the modified TP-D type discharge. In the experiments, we have carried out the spectroscopic measurements of the detached recombining helium plasma in the downstream region (at the axial position of $X = 1.72$ m from the discharge anode electrode) near the end plate ($X = 2.05$ m) using an absolutely calibrated optical detection system as shown in Fig. 1. The optical multichannel analyzer (OMA) is composed of a 0.75 m SPEX spectrometer and a 2D CCD camera. The neutral gas pressures in the divertor test region were monitored with baratron pressure gauges at three different axial positions of the test region; the entrance ($X = 0.10$ m), the upstream (X = 1.06 m) and the end plate. The neutral pressure can be controlled by introducing a cooling gas near the end plate and/or changing the pumping speed of turbo molecular pumps. The upstream pressure P_u was used as a standard pressure in the test region.

3. Experimental results and discussion

A typical continuum spectrum observed in the downstream region at $P_u \sim 6.1$ mTorr is shown in Fig. 2. Long exposure time (60 s) can make it possible to observe clear continuum emission owing to steady state detached plasmas. The T_e can be determined by comparing the observed spectrum with the theoretically calculated one using a formula given in Ref. [9]. In this calculation, the free-bound transitions into the four states of principal quantum number $p = 2$ were considered. A plasma diameter of 25 mm, measured using a fast scanning probe, was used for the evaluation. In Fig. 2, the measured continuum emission is found to match the calculated one (long-dashed line) with parameters, $T_e = 0.23$ eV and $n_e = 2.24 \times 10^{19}$ m^{-3}.

In the collision-dominated plasma, where the partial local thermodynamic equilibrium is satisfied, the electron population in the highly excited levels obeys a Boltzmann relation:

$$\frac{n_k}{n_i} = \frac{g_k}{g_i} \exp\left(-\frac{E_k - E_i}{k_B T_e}\right), \quad (1)$$

where n, g and E are the population density, the statistical weight and the energy in a state, respectively. The indexes i and k denote the lower and upper levels, respectively. k_B is the Boltzmann constant. Using this relation, T_e was obtained from the intensities of the observed emission lines of $2^3P - p^3D$ $(p = 6, \ldots, 10)$. Fig. 3 shows the population densities per statistical weight normalized by the value of $p = 10$, which are obtained from a experimental data at $P_u \sim 6.1$ mTorr, corresponding to Fig. 2. The slope gives T_e of 0.16 eV.

Fig. 4 shows the neutral pressure dependence of T_e, where T_{ec} means T_e obtained by the continuum method and T_{eb} by the Boltzmann plot method, and the electron density n_e is also calculated from the absolute value of continuum emission at the discharge current of 80 A. With increasing the neutral pressure from 4 to 12 mTorr, the both T_{ec} and T_{eb} monotonically decreased, however, T_{ec} is higher than T_{eb} at 4 mTorr $< P_u <$ 10 mTorr. The reason of this discrepancy between T_{ec} and T_{eb} is so reproducible, which will be discussed later. At $P_u > 10$ mTorr, T_{ec} and T_{eb} become the same value of 0.12 eV. n_e showed a typical roll-over often observed in divertor

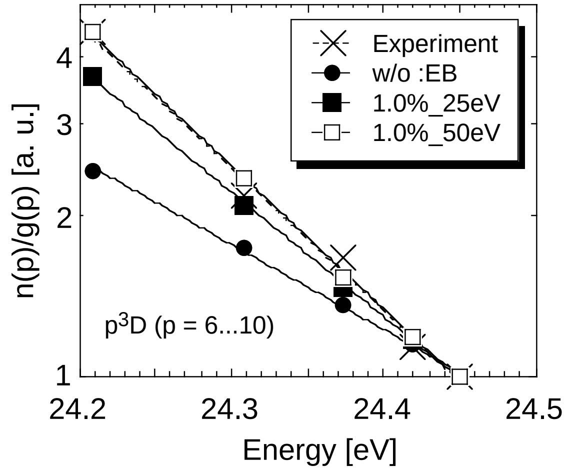

Fig. 3. Population densities (at p^3D, $p = 6, \ldots, 10$) per statistical weight normalized at $p = 10$. Crosses show experimental data at $P_u \sim 6.1$ mTorr ($T_e \sim 0.16$ eV). Closed circles are the calculated results using a collisional radiative model with $T_e = 0.23$ eV, $n_e = 2.24 \times 10^{19}$ m^{-3} and $n_n = 2.5 \times 10^{20}$ m^{-3}. Closed ($T_e \sim 0.19$ eV) and open ($T_e \sim 0.16$ eV) squares are calculated with electron beam components of the density $n_b = 0.01 n_e$ and the energy 25 and 50 eV, respectively.

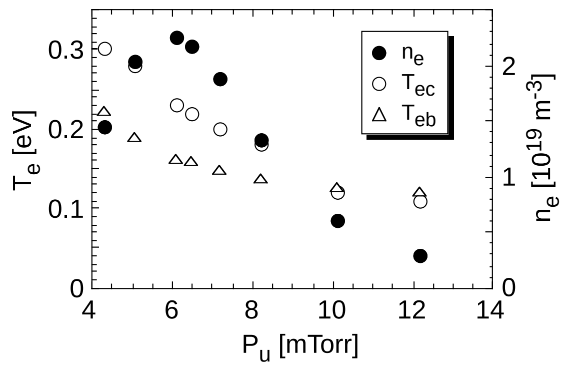

Fig. 4. Neutral pressure dependence of the electron temperatures and the density (closed circles) at downstream. The temperatures were evaluated from the continuum (open circles) and the Boltzmann plot (open triangles) methods.

plasmas of tokamaks and a subsequent decrease. A higher neutral pressure results in a higher n_e due to ionization at the upstream region. The charged particles flow into the downstream region where a density rise is observed at low pressure ($P_u \leqslant 6$ mTorr). At a higher neutral pressure, the main recombination region moves to the upstream region and then n_e decreases at the downstream region.

Now we will discuss the deviation between T_{ec} and T_{eb} mentioned above. Various reasons may be considered, but we would like to concentrate on the influence of the deviation from the Maxwellian distribution on the evaluation of bulk low T_e by the spectroscopic method. In general, there is a small amount of non-thermal energetic electrons in plasmas due to several reasons, such as the primary electrons in the discharge, and additional heating in fusion devices.

In order to reveal effects of energetic electron components on T_e determination with the Boltzmann plot, we calculated the population densities by using a collisional radiative (CR) model for neutral helium [10,11] at the parameters of $T_e = 0.23$ eV and $n_e = 2.24 \times 10^{19}$ m^{-3}, obtained from the continuum method, and $n_n = 2.5 \times 10^{20}$ m^{-3} with and without the energetic electron components. It is found from Fig. 3 that energetic electron components lead to an increase in the population densities mainly in the lower excited levels due to the excitation from the ground state, resulting in a lower T_e from the Boltzmann plot method. The open squares, calculated with the energetic electron density $n_b = 0.01 n_e$ and the energy of 50 eV, are in an agreement with the experimental data. In general, we can say that the Boltzmann plot method gives lower T_e than that in the continuum method when the energetic electron components exist. Therefore T_{eb}s became lower than T_{ec}s at 4 mTorr $< P_u <$ 10 mTorr. On the other hand, in the higher pressure of $P_u >$ 10 mTorr, T_{eb}s are nearly equal to T_{ec}s as shown in Fig. 4, probably due to a decrease in the energetic electron components. More detailed discussion including several effects such as metastable levels will be reported soon. On the other hand, the influence of energetic electrons on the continuum method is thought to be small because the energetic electrons around 50 eV cannot contribute to the continuum emission as shown, as a short dashed line, in Fig. 2.

Until now, the effects of local non-Maxwellian distribution function on the evaluation of bulk low T_e have been discussed. We should notice that when there is a T_e's profile along a line of sight, T_{eb} would become lower than T_{ec} because a superposition of emission from high and low T_e regions leads to similar effects to those of energetic electron components for the Boltzmann plot method mentioned above.

Finally, we would like to briefly discuss what determines T_e in the recombination region, which is denoted as T_e^* hereafter, in the divertor simulator. The T_e^* has been discussed using a 1D simple analytical model in Ref. [12]. That analytical model considers thermal conduction as the electron heat flux parallel to the magnetic field and the electrons are assumed to be cooled down due to electron–ion temperature relaxation process. The plasma flux is described in a diffusive approximation. Under these assumptions, the electron energy balance and plasma continuity equations lead to a formula for T_e^* as follows:

$$\frac{3.2}{3}\frac{v_{iN} v_{EIR}(n_e, T_e^*)}{[v_{ei}(n_e, T_e^*)]^2}\left(\frac{M}{m}\right)^2 = 1, \quad (2)$$

where v_{iN}, v_{EIR} and v_{ei} are the ion–neutral collision, the EIR and the electron–ion collision frequencies, respectively. M and m are the ion and the electron masses, respectively. For helium, it was reported that Eq. (2) gave $T_e^* \sim 0.15$ eV at the neutral pressure of 10 mTorr. This value is similar to a typical value of about 0.2 eV in our experiment.

4. Summary

We have evaluated the electron temperature in detached recombining plasmas of NAGDIS-II with the spectroscopic methods. A comparison of the electron temperatures obtained by the continuum and the Boltzmann plot methods shows that the Boltzmann plot method is strongly influenced by the energetic electron components compared with the continuum method. Therefore, in the presence of energetic electron components, the Boltzmann plot method gives lower electron temperature than that in the continuum method.

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