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Determination of electron temperature and density at plasma edge in the Large Helical Device with opacity-incorporated helium collisional-radiative model

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ABSTRACT

Spectra of neutral helium in the visible wavelength range are measured for a discharge in the Large Helical Device (LHD). The electron temperature (T_e) and density (n_e) are derived from the intensity distribution of helium emission lines. For that purpose, a collisional-radiative model developed by Sawada et al. [Plasma and Fusion Res. 2010;5:001] which takes the reabsorption effect into account is used. It is found that incorporation of the reabsorption effect is necessary to obtain a set of T_e and n_e giving consistent line intensity distribution with the measurement, and that those parameters obtained vary as the line-averaged n_e changes in the course of time. The position where the helium line emission dominantly takes place is located with the help of T_e and n_e profiles measured by the Thomson scattering system. The result indicates that the emission position is almost fixed at the place where the connection length of the magnetic field lines to the divertor plate leaps beyond 10 m. Because intense neutral atom line emission suggests the vigorous ionization of neutral atoms, the helium line emission location determined here can be regarded as the effective boundary of the plasma.

1. Introduction

The measurement of the electron temperature T_e and density (n_e) which uses neutral helium emission lines has become a widespread technique for various kinds of laboratory plasmas [1–7]. This method is based on the comparison of measured line intensity ratios with those calculated by the collisional-radiative (CR) model [8,9]. The reliability of the obtained results depends on the accuracy of the atomic data, the excitation cross section data [10–12] in particular, used in the CR model. In such circumstances, great efforts have been made to improve the calculation technique of the cross section data, and consequently the presently available cross section data are thought to be accurate enough for practical use in the CR model calculation.

Nevertheless, we still observe that derived T_e and n_e have significant discrepancy from those measured by the electrostatic probes [3] or that the parameters derived from a limited number of emission lines yield a false intensity distribution for the other observed lines [9]. One conceivable reason is the influence of the reabsorption effect. Dealing with the reabsorption effect is however difficult because it is essentially a non-local problem, namely, the emission and absorption processes at different locations are related to each other so that the self-consistency over the entire plasma volume must be considered.

We have previously developed an iterative computational code which solves the radiative transfer equation

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coupled with the collisional-radiative rate equations. Although that attempt has been successful for a parallel plate plasma [13] or a plasma having cylindrical symmetry [14], implementation for a complicated plasma structure requires enormous computational resources so that frequent use for the experimental data analysis is difficult.

Instead, we have proposed a simple but adequate method to incorporate the reabsorption effect in the CR model [15], where the photoexcitation rate from the ground state due to the reabsorption effect is adopted as a fitting parameter as well as T_e and n_e when the measured line intensity distribution is fitted with the CR model calculation. This method has been applied to an RF plasma ($n_e \sim 10^{16}$ m^{-3}) at Shinshu University, where a satisfactory agreement between the measured and fitted intensity distribution has been obtained with a set of reasonable parameters.

However, because n_e is rather low in this RF plasma, the influence of the reabsorption effect on the excited level populations is limited on the levels directly populated by the photoexcitation process, i.e., the n^1P states with $n \geq 2$. In this paper, we examine this diagnostic technique through applying it for a plasma in the Large Helical Device (LHD), a heliotron-type fusion experimental device, which generates a rather high n_e plasma so that the influence of the reabsorption effect over the entire excited levels is expected.

2. Experimental setup

The measurement is made for an LHD discharge with $R_{ax} = 3.9$ m and $B_{ax} = 2.54$ T, where R_{ax} and B_{ax} are the magnetic axis radius and the magnetic field strength on the magnetic axis, respectively. The spectroscopic measurement is performed with a single line-of-sight as shown in Fig. 1. One end of an optical fiber having 100 μm diameter is located at the observation port. The field of view is collimated with a lens so that the spatial resolution is about 30 mm. The other end of the optical fiber is put at the entrance slit of a 50 cm Czerny–Turner-type spectrometer (Chromex 500is) equipped with a 100 grooves/mm grating. A CCD (Andor DU-420UV) is used as the detector. The absolute sensitivity of the total observation system has been calibrated with a standard lamp system.

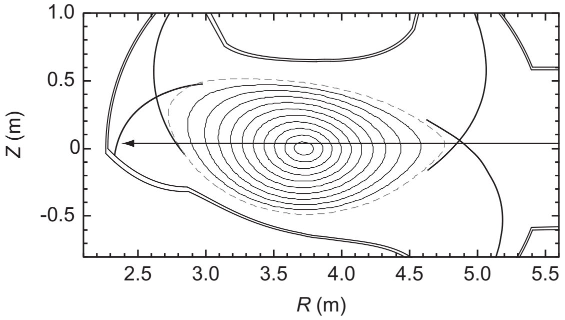

Fig. 1. Poloidal cross section of the plasma with magnetic flux surfaces for the present measurement. The line-of-sight is shown with the arrow.

The viewing chord passes through the horizontally elongated poloidal cross section of the plasma as shown in Fig. 1. It is known that line emission of neutral helium is concentrated at the plasma boundary and the radial extent of line emission region is no more than several centimeters [16]. In the present line-integrated measurement, the measured line intensity comprises line emissions at the two boundary regions on the line-of-sight, namely, at the inboard-side ($R \sim 2.8$ m) and at the outboard-side ($R \sim 4.9$ m) of the plasma.

Fig. 2 shows the temporal development of the discharge for the present study. First, a small amount of hydrogen gas is supplied in the vacuum vessel and the electron cyclotron heating (ECH) is given to produce a seed plasma. Then three neutral beams (NBs) take over the heating from ECH and sustain the plasma.

During the injection of NBs, helium gas is continuously puffed so that n_e is built up. The dashed-line in Fig. 2(b) indicates the voltage in arbitrary units applied to the piezo-valve at the gas-puff nozzle, which should be proportional to the gas-puffing rate. The line-averaged electron density $\overline{n}_e$ increases monotonically during the period of the gas-puff, while the central electron temperature T_{e0} is lowered correspondingly. The T_e profile is

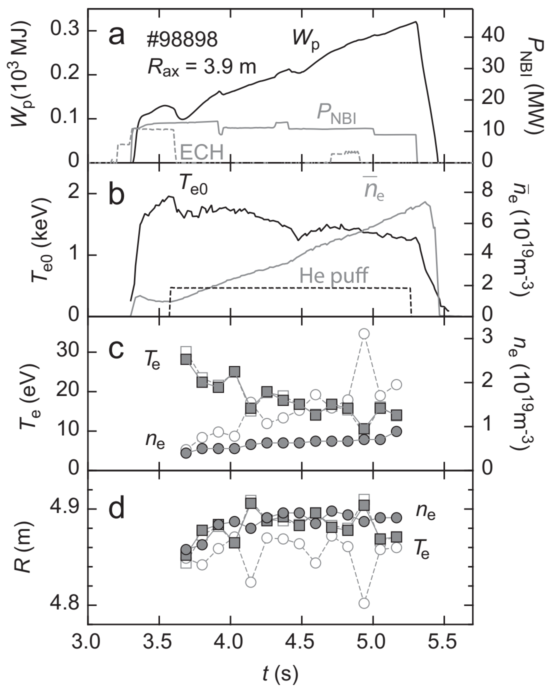

Fig. 2. Temporal development of the discharge for the present observation. (a) Stored energy (W_p, black solid line) and neutral beam power (P_{NBI}, gray solid line), and electron cyclotron heating power in arbitrary units (gray dashed line). (b) Central electron temperature (T_{e0}, black solid line) and line-averaged electron density ($\overline{n}_e$, gray solid line), and gas puff rate in arbitrary units (black dashed line). (c) T_e (squares) and n_e (circles) determined in the present analysis with (filled) and without (open) the reabsorption effect. (d) Radial locations of line emission determined from the derived T_e and n_e and their radial profiles by Thomson scattering system where the filled and open symbols correspond to with and without reabsorption effect, respectively.