Edge carbon transport study with space-resolved VUV spectroscopy in HL-2A Tokamak

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Edge impurity transport in toroidal devices is of great concern for the control of impurity concentration and the mitigation of excessive divertor heat load, which are mainly affected by the edge magnetic field structure in addition to the edge temperature and density profiles. It is then indispensable to deeply understand the edge impurity behaviors in both the experimental and theoretical studies. However，difficulties on the absolute intensity measurement of radial profile for and impurity line emissions in vacuum ultraviolet (VUV) wavelength range and on the impurity transport modeling in the edge region (r/a >0.8) generally make the study harder. In the present work the edge impurity transport has been studied for carbon in the outer region of core plasma of HL-2A tokamak (R/a = 165/40cm) based on the radial profile measurement of CIII (977 Å: $2s^2\ ^1S_0$-$2s2p\ ^1P_1$), CIV (1548 Å: $2s\ ^2S$-$2p\ ^2P$) and CV (2271 Å: $1s2s\ ^3S$-$1s2p\ ^3P$) using a space-resolved VUV spectrometer[1], of which the intensity is absolutely calibrated with bremsstrahlung continuum.

Since the charge state of impurities increases with electron temperature, the impurity ions having lower (higher) ionization energy, E_i, distribute in outer (inner) region of plasmas. The radial locations of CIII, CIV and CV line emissions are obviously different because of the different ionization energies of CV (E_i=392 eV), CIV (64 eV) and CIII (48 eV). The radial profiles of them measured from the HL-2A plasma are plotted in Fig. 1(a). It shows that the C^{2+} and C^{3+} are mostly located at the edge of SOL and near the LCFS, respectively, while the C^{4+} exists in the plasma core. Therefore, the intensity ratio of CIV to CIII can be used to characterize the impurity screening in the SOL region. On the other hand, CIV can indicate the carbon influx at LCFS and CV can be a proxy to indicate the ions experienced the transport in the core plasma through the LCFS.

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In general, the emissivity of these spectral lines is expressed as follows:

$$I^Z(T_e,n_e)=n_e n_{imp}^Z\ L^Z(T)\ , \qquad (1)$$

where $n_{imp}{}^Z$ is the density of impurity ions with ionization stage of Z and $L^z(T)$ is the emission coefficient. The emission coefficient of these lines is basically insensitive to the electron density in the range of $n_e=10^{18}\sim10^{20}$ m^{-3}. The emission coefficients for CIII, CIV and CV are plotted in Fig. 1(b) as a function of electron temperature. The impurity flux can be calculated using an 1D impurity transport code STRAHL[2]. The flux is modeled as the sum of a diffusive term and a convective term:

$$\Gamma_Z(r)=-D(r)\frac{\partial n_Z(r)}{\partial r}+V(r)n_Z(r)\ , \qquad (2)$$

where D(r) and V(r) are assumed to be time independent. The code uses prescribed radial profiles of transport coefficients to resolve the time-dependent continuity equations for all the ionization stages of the interesting element:

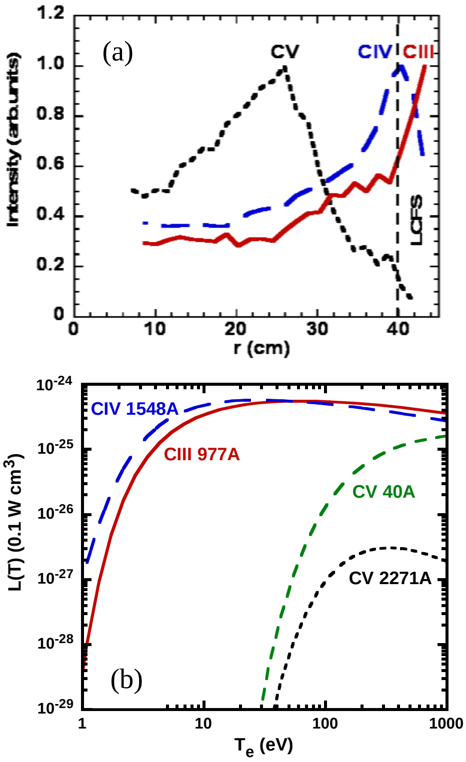

Fig.1. (a) Normalized radial profiles and (b) Emission coefficients of CV, CIV and CIII.

$$\frac{\partial n_z}{\partial t}+\nabla\Gamma_z=n_e(S_{z-1}n_{z-1}+\alpha_{z+1}n_{z+1})-n_e n_z(S_z+\alpha_z)+s_z\ , \qquad (3)$$

where S_Z and α_Z denote the ionization and recombination rate coefficients of the ionization stage z, respectively, and s_Z is the external source. In general, D and V cannot be determined separately in the intrinsic impurity transport study. The validity of the transport coefficients is also limited to the inner part of plasma (r/a < 0.8) because the determination of D and V becomes questionable due to increase in the uncertainty at plasma edge. That may be caused by the failing description of the neutral source in the one-dimensional model.[3] By adding some additional constraints on the influx of impurities near the edge, however, the transport coefficients of impurities can still be determined by these 1D codes. In this context, D and V are simply assumed to be spatially constant and a linear dependence on r (V(r)=V(a)×r/a), respectively. In order to analyze the spectroscopic data with this code, the influence of D and V(a) on the radial profile of CV are investigated by changing the values of D and V(a) separately. The results are presented in Fig. 2, where the intensity and peak position of CV are plotted as a function of D and V(a). It can be seen in Fig. 2(a) that the CV line intensity increases and its peak position shifts toward plasma center when D increases from 0.3 m^2/s to 4 m^2/s. On the other hand, the CV intensity decreases and its peak position keeps nearly unchanged when V(a) increases from -4 m/s to 8 m/s, as shown in Fig. 2(b). It clearly shows that the effect of D and V(a) on the carbon impurity transport are significantly different. Furthermore, when the intensity ratio of CV to CIV is considered, the ratio is very sensitive to only the value of V(a), as shown in Fig. 2(c). This could also help to determine the D and V(a) in the present study. In general, the ratio of CV to CIV decreases by a factor of three when ECRH power is applied to the Ohmic heating plasma in HL-2A. In order to describe the experimental results, only the consideration of D was not enough for the case of ECRH L-mode plasma. Therefore, we argued that the edge impurity transport coefficients could be determined by reproducing the experimental spectroscopic data on the radial profile of CV and the ratio of CV to CIV. Here, the measured CIV is also used as a constraint on the source term for the ECRH discharge. All of the key parameters used to determine the D and V(a) can be provided by the present VUV spectrometer in HL-2A.

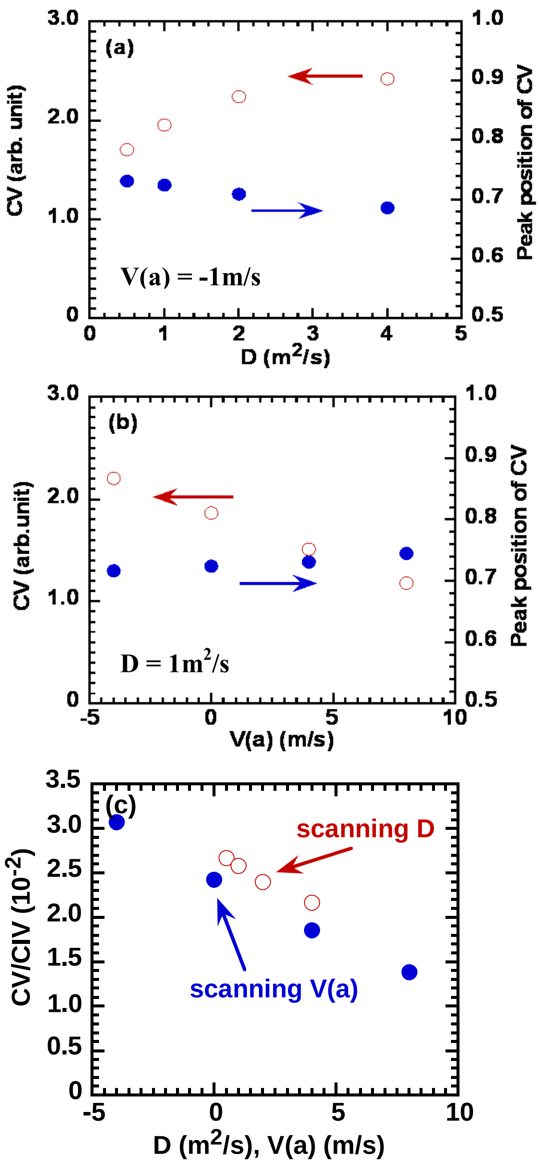

Fig2. Intensity and peak location of CV as a function of (a) D with fixing V(a)=-1m/s and (b) V(a) with fixing D=1m^2/s, and (c) CV/CIV as function of D and V, respectively.

With the initial analysis of the transport coefficients based on the experimental results using the laser blow-off method in HL-2A[4] a

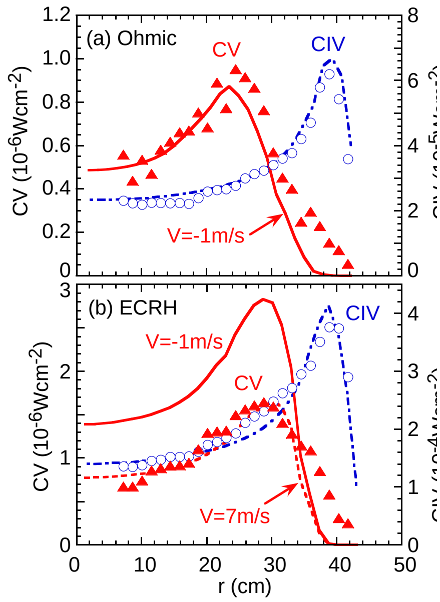

Fig.3. Radial profiles in (a) Ohmic and (b) ECRH phases with simulation (V(a) = -1m/s (dot-dash and solid lines) and V(a) = 7 m/s (dashed lines).

self-consistent transport solution is obtained by carefully adjusting the transport parameters until a good fitting of these C line emissivity profiles are simultaneously obtained. The result on Ohmic plasmas is shown in Fig. 3(a). A good agreement is obtained between the simulation (lines) and the experiments (symbols), when D = 0.6 m^2/s and V(a) = -1 m/s are adopted. The observed density dependence of CV/CIV in the Ohmic discharge can be also well explained with these coefficients. The result on ECRH plasmas is shown in Fig. 3(b). The CV profile (solid line) simulated with the Ohmic transport coefficients reveals a larger intensity compared with the experiments (closed triangles). The transport property of C^{4+} must be modified when ECRH is applied. Based on the results of Fig. 2 the increase of V(a) is needed. A reasonable fitting can be obtained when the convective velocity is changed to V(a) = 7 m/s, as shown in the dashed lines in Fig. 3(b). The positive value of the convective velocity means an outward flux of carbon ions in the plasma core, while the result in Ohmic plasmas shows an inward flux. The ECRH heating in HL-2A shows the impurity reduction in the plasma core due to the enhanced transport in addition to the edge impurity buildup. The present result is also consistent with previous experimental results from ECRH discharges in other tokamaks.[5]

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