Observation of edge impurity screening in L- and H-mode discharges with additional ECH and NBI heating of HL-2A

Z.Y.Cui[1)], S.Morita[2)], Y.D.Gao[1)], P. Sun[1)], Y.Xu[1)], Z.B.Shi[1)], H.J.Sun[1)], W.W.Xiao[1)], W.Y.Hong[1)], Y.Zhou[1)], Y.D.Pan[1)], M.Kobayashi[2)], X.T.Ding[1)], Q.W.Yang[1)], X.R.Duan[1)]

[1)]*Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China*

[2)]*National Institute for Fusion Science, Toki 509-5292, Gifu, Japan*

Edge impurity transport in toroidal devices is of great concern for the control of the impurity concentration and the mitigation of the excessive divertor heat load, which mainly depends on the edge magnetic field structure in addition to the edge temperature and density. Deeper understanding on the edge impurity behaviors is desired in both fields of the experiment and theory, in particular, to establish the basis applicable to reactor-size plasma such as ITER. Active control of the core impurity profile has been reported in different heating scenarios of electron- and ion-heating regimes[1,2]. Several experiments indicated that the discharge operation in the electron-heating regime could decontaminate the impurities from the plasma core more efficiently than that in the ion-heating regime. However, the edge impurity behaviors have been seldom reported related to such different heating scenarios. In the present paper the edge impurity transport has been investigated based on carbon emissions of CIII (977Å: $2s^2\,{}^1S_0$-$2s2p\,{}^1P_1$), CIV (1548Å: $2s\,{}^2S$-$2p\,{}^2P$) and CV (2271Å: $1s2s\,{}^3S$-$1s2p\,{}^3P$) measured with space-resolved VUV spectroscopy [3] during the electron heating via electron cyclotron resonance heating (ECRH) and the ion heating via neutral beam (NB) heating in the HL-2A tokamak (R = 165cm and a = 40cm). The discharges are mainly operated at high toroidal magnetic field of $B_t = 2.4$T with plasma current of $I_p = 200$-450kA under the presence of single-null closed divertor configuration.

The screening effect of the edge impurity can be measured with the intensity ratio of CV to CIII+CIV since the impurity ions having higher or lower ionization energy, E_i, exist in the inner or the outer region of edge plasmas, respectively. The CIII and CIV ions are located in an extremely low temperature region of $T_e < 60$eV, while the CV ions are located in a relatively high electron temperature region of $60 < T_e < 400$eV. Therefore, the radial location is clearly separated between the CV and CIII (or CIV). The measured profiles of

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1 Email: cuizy@swip.ac.cn

CIII, CIV and CV evidently indicate that these ions are located at certain radial positions according to their ionization energies. In fact, the CV (E_i = 392eV) is located inside the last closed flux surface (LCFS) and the CIV (E_i = 64eV) and CIII (E_i = 48eV) are located in the scrape-off layer (SOL). Thus, the CIII and CIV can be the source term indicating the carbon influx at the outside of LCFS and the CV can be regarded as the ions already experienced the radial transport through the LCFS. The intensity ratio of CV to CIII+CIV represents the degree of impurity screening.[4,5]

The ECH system in HL-2A consists of four gyrotrons (68GHz, 4×0.5MW) and is operated at the first harmonic resonance with O-mode propagation when B_t = 2.4T and at the second harmonic resonance with X-mode propagation when B_t = 1.2T. The NB heating system consists of four ion sources and provides the maximum power of 1.5MW at beam energy of E_b = 40keV for tangential injection. Since in the present study the ratio of the beam energy to the electron temperature is smaller than 20, most of the NB heating power is given to the bulk ions.

The edge impurity transport behavior is expressed with the ratio of CV to CIII+CIV, as shown in Fig. 1. The ratio drastically decreases when the ECH heating is turned on (see Fig.1(a)). It is kept at the small value around 0.01 during the ECH heating. The ratio is reduced to one-third in the ECH phase compared to the ohmic phase. The substantial reduction of the core impurity influx following enhancement of the impurity screening during the ECH phase is also verified for the modulated ECW power experiment with B_t = 1.3T or B_t = 2.4T. On the contrary, the increase in the ratio is observed during the NB heating phase as shown in Fig.1(b). This increment of the ratio continues until the end of the NB pulse.

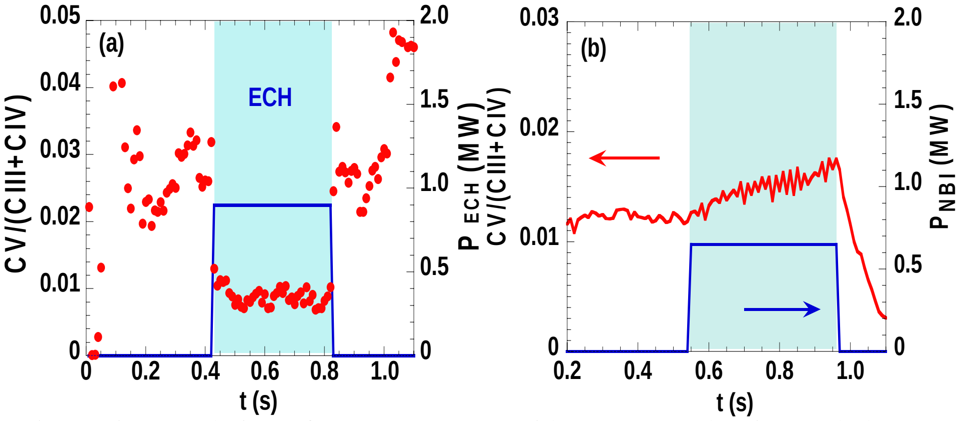

Fig.1. Time evolution of CV/(CIII+CIV) with (a) ECRH heating and (b) NBI heating.

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1 Email: cuizy@swip.ac.cn

The ratio of CV/(CIII+CIV) is also studied for the H-mode regime, which is achieved by simultaneous heating based on the ECH and NB pulses. The ratios obtained in the present study are summarized in Fig. 2 as a function of n_e including different plasma discharge conditions, i.e., ohmic discharge, L-mode with ECH (or NBI), L-mode with ECH+NBI and H-mode with ECH+NBI. The ohmic discharges indicate the smooth density dependence of the ratio because the reproducibility among the discharges is quite good. The impurity screening is clearly seen at $n_e < 2\times10^{19}m^{-3}$. Behaviors of the ratios in the case of L-mode with NBI are also very similar to the ohmic case. However, the ratios behave very differently when the ECH pulse is applied. The density dependence of the ratio is extremely large in ECH discharges at $n_e < 1\times10^{19}m^{-3}$ and the ratio takes very small values less than 0.005 at $n_e = 1\times10^{19}m^{-3}$. This tendency is also similar to the case of L-mode with ECH+NBI. The lowest ratio is obtained in the H-mode discharges at relatively high-density range of $1.5 \le n_e \le 2.5\times10^{19}m^{-3}$ suggesting a sudden change of the edge impurity transport. These experiments show that the two heating regimes seem to have significantly different effects on the edge impurity transport.

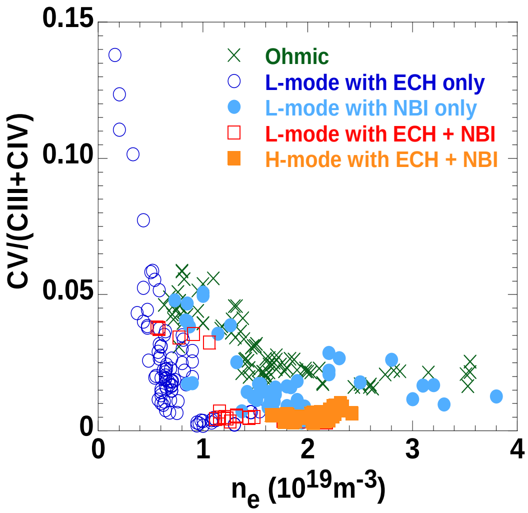

Fig.2. Ratio of CV to CIII+CIV as a function of n_e in Ohmic, ECH and NBI discharges with L-mode and ECH+NBI discharges with L- or H-modes.

Radial profiles of electron temperature and density are examined to study the effect of the electron- and ion-heating regimes on the impurity transport. The electron temperature profile T_e (r) is measured by ECE diagnostic. It is clearly observed that the electron temperature quickly increases all over the plasma radius when the ECH pulse is applied to the ohmic discharges, as shown in Fig. 3(a). In contrast to this the electron temperature does not change in the NBI phase (also see Fig. 3(a)). The edge electron temperature in the SOL is measured by Langmuir probes. The result also indicates a significant increase in the ECH phase. The electron density profiles in the central region of plasmas are measured by 8-chord far infrared interferometer. The density generally decreases in the ECH phase and

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[1] Email: cuizy@swip.ac.cn

increases in the NBI phase, as shown in Fig. 3(b). The edge density profiles are measured by a microwave reflectometer with 26.5-40GHz, which covers density range of 0.8 to $2.0\times10^{19}m^{-3}$. The measured edge density profiles can be smoothly connected to the core density profile measured by the laser interferometer. The edge ion temperature is measured by VUV spectral line of CV (2270.89Å). A typical result is presented in Fig. 3 (c). It is clear that the edge ion temperature increases during the NBI phase.

The impurity behavior in SOL can be dominantly explained with the parallel transport along the magnetic field line, in which the balance between the friction and the thermal forces is of great important[6], whereas the impurity transport is dominated by the perpendicular transport in the plasma core. When the edge temperature is sufficiently high and the CV locates near the LCFS, the intensity ratio of CV/(CIII+CIV) express the impurity screening in the SOL. If the ratio also indicates the impurity screening in the H-mode discharges, another process except the friction force seems to be necessary to explain such small intensity ratio. The detailed comparison of the data will be done in the future based on the modeling simulation.

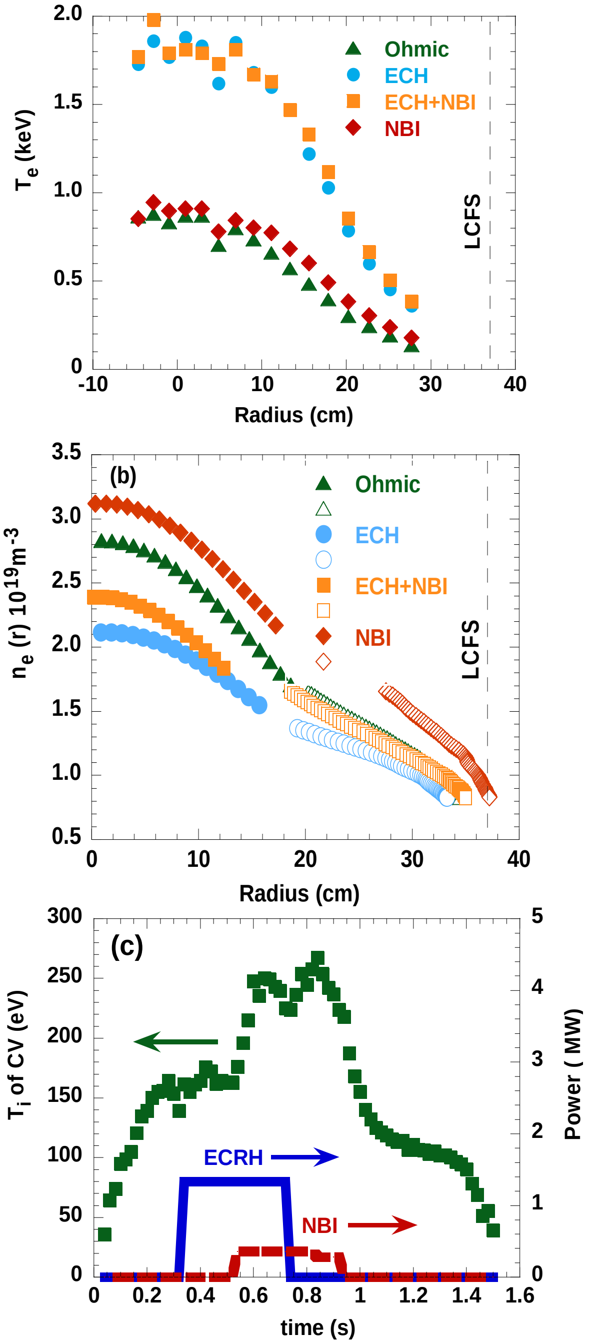

Fig.3 (a) T_e profile measured by ECE diagnostic, (b) n_e profile measured by 8-chord interferometer (closed symbols) and by microwave reflectometer (open symbols) and (c) time evolution of edge T_i from CV (227.09 Å).

References

[1] C.Angioni, et al., Phys. Plasmas, **14**(2007) 055905.
[2] M.E.Puiatti, et al., Phys. Plasma, **13**(2006)042501.
[3] Z.Y.Cui, et al., Rev. Sci. Instrum., **81**(2010)043503.
[4] S.Morita, et al., Plasma Sci. Tech., **11**(2009)402.
[5] M.B.Chowdhuri, et al., Phys. Plasmas, **16**(2009)062502.
[6] M.Kobayashi, et al., 23rd IAEA FEC 2010, EXD/6-5Ra.

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