Impurity transport of ion ITB plasmas on LHD

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Abstract. Impurity hole, which is an extremely hollow profile of carbon impurity, is observed associated with increase of ion temperature gradient in the Large Helical Device (LHD). Difference of convection velocity in the magnetic axis position is clearly observed. It is suggested that the impurity hole becomes strong as the magnetic axis is shifted outward. The dependence of the impurity hole on the charge number, *Z*, is observed and the profile of higher *Z* impurity becomes more hollowed.

1. Introduction

Simultaneous achievement of improved energy confinement and low impurity confinement is one of the crucial issues to realize the plasma relevant to nuclear fusion because impurities cause reduction of the fusion power density by enhancing the cooling of the plasma with radiation and also by diluting the hydrogen fuel. Impurities tend to accumulate in the plasma with an improved confinement mode such as H-mode and internal transport barriers (ITB) in tokamaks. Although impurity accumulation can be avoided in the ELMy H-mode discharges, impurity accumulation is still a problem in the discharges of the ELM-free H-mode and the discharges with an internal transport barrier. On the other hand, temperature screening effect due to an ion temperature gradient is expected in tokamaks and the outward convection of impurities was confirmed in the improved confinement plasma with a weak density gradient and a strong ion temperature gradient on DIII-D [1]. Impurity accumulation can be avoided by density profile control with an intensive gas puff, and high energy and low impurity confinement times are demonstrated in high density H-mode (HDH) plasma in the Wendelstein 7-AS stellarator [2]. Radial electric field is strongly affected to the impurity transport in non-axisymmetric system. The impurity convection can be outward and the impurity density can be hollow due to the positive radial electric field in the electron-ITB plasmas, where the electron temperature is much higher than the ion temperature. Inward convection of impurities is expected from neoclassical theory in the plasma with a high ion temperature gradient because of the negative radial electric field in the ion-ITB plasma by assuming the radial electric field is strongly affected to the impurity transport also in the case of negative electric filed. An extremely hollow impurity profiles due to outward impurity convection is experimentally observed in the plasma with a steep gradient of ion temperature in LHD. Although the outward impurity convection is a consistent to the convection with the temperature screening, it is difficult to conclude that the dominant player on the impurity transport in the high ion temperature discharges is neoclassical transport or turbulence transport from only the direction of the impurity flux because there are only two directions which can be observed in experimentally. We have to observe the behaviors of various species of impurity profiles in the plasmas with various conditions of magnetic field.

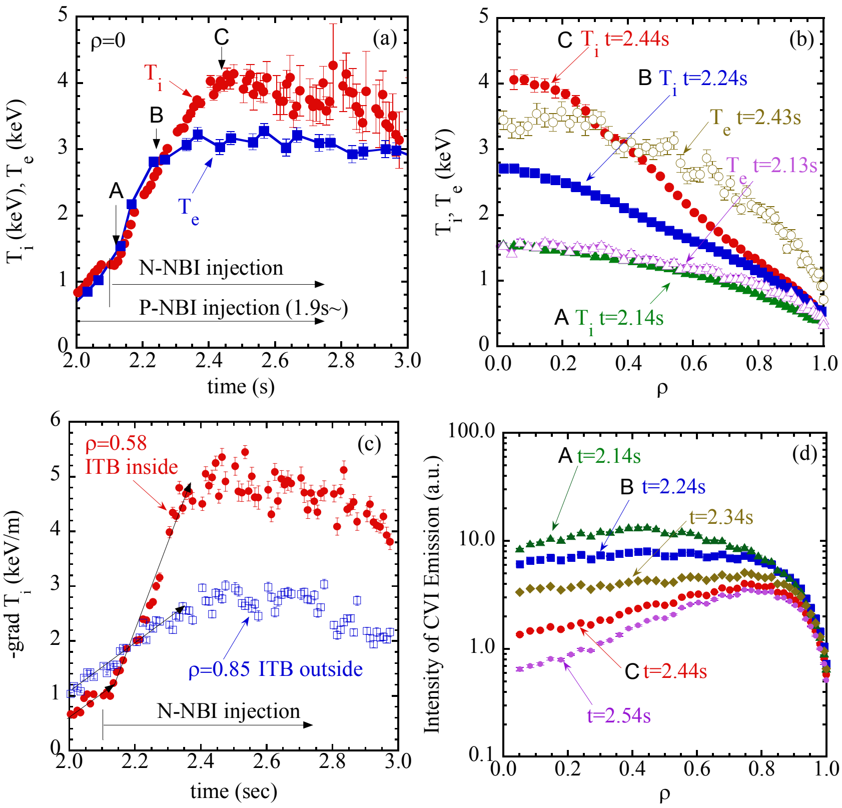

FIG. 1. (a) Time evolution of ion temperature and electron temperature. (b) Radial profiles of ion temperature and electron temperature. (c) Time evolution of ion temperature gradient. (d) Radial profiles of charge exchange emission of carbon.

2. Ion ITB discharge on LHD

LHD is a heliotron-type device equipped with three high energy beam lines that have the beam energy of 180keV with negative ion sources (N-NBI) and a low energy beam line that has the beam energy of 40keV with positive ion sources (P-NBI). The high energy beams have the advantage in the electron heating, and these are injected to the plasma tangentially. The low energy beam has the advantage in the ion heating and also in the charge exchange spectroscopy and injected to the plasma perpendicularly. The ion temperature, toroidal flow velocity, poloidal flow velocity, and intensity of the charge exchange emission from carbon impurity (CVI, λ=529.05nm) are measured with the charge exchange spectroscopy using the P-NBI as a probe beam. In order to subtract the background emission, which is cold component from the plasma periphery, the beam is modulated on and off. The radial electric field can be derived from the poloidal flow velocity. Carbon density can be derived from the intensity of the emission from carbon impurity by charge exchange between the fully ionized carbon in plasmas and the neutral beam. Figures 1 (a) and (b) show the time evolution and radial profiles of ion and electron temperature in the plasma with the magnetic axis R_{ax}=3.6m, the magnetic field strength B=-2.75T, the coil pitch parameter γ=1.254, and the canceling rate of the quadrupole filed B_q=100%, respectively. Steep gradient of ion temperature is produced at the mid-radii, and the ion temperature becomes higher than the electron temperature at the center of the plasma. The higher ion temperature plasma is produced by injection of N-NBI into the plasma sustained by the P-NBI. After the N-NBI injection, the ion temperature profile is changed from the hill shape, which is moderately increased toward the center, to the bell shape, which is a peaked profile with a steep gradient at the middle of the plasma radii, while

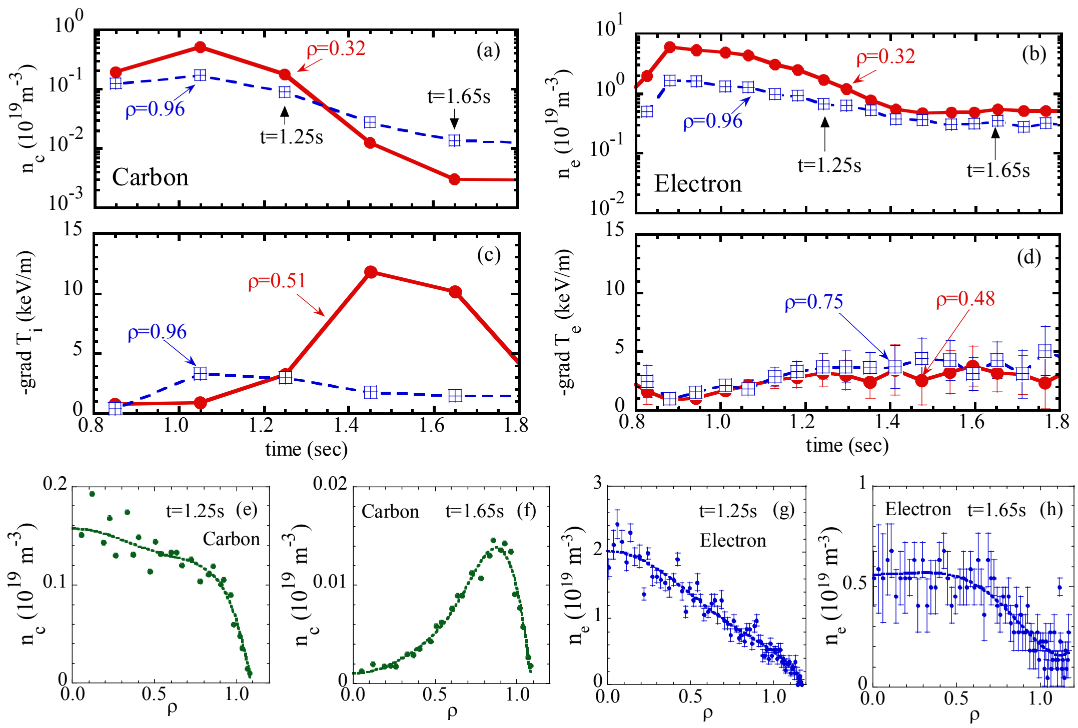

FIG.2. Overview of the discharge with the impurity hole from Ref.[3]. Time evolutions of (a) carbon density, (b) electron density, (c) ion temperature gradient, and (d) electron temperature gradient. Radial profiles of carbon density (e) before and (f) after the impurity hole developed. Radial profiles of electron density (g) before and (h) after the impurity hole developed.

the electron temperature is moderately increased toward the center as shown in Fig.1 (b). We are interested in the position where the transport barrier exists. It is difficult to define the ITB foot in the ion ITB observed in the LHD plasma, because the barrier is not localized and the ion temperature gradient is seemed to be gradually increased toward the plasma center. The time evolution of the ion temperature gradient shows clear difference between inside and outside of the improved confinement region as shown in Fig.1 (c). The gradient is increased with the rate of 5keV/m/s before the N-NBI injection both near the mid radii (ρ=0.58) and near the edge (ρ=0.85). The rate changes to 15keV/m/s after the N-NBI injection near the mid radii while the rate is not changed near the edge. The boundary between the region where the gradient changes to large and the region where the gradient kept constant is the boundary of the improved confinement region. Although we have discharges that the gradient near the edge decreases after the ion ITB formation, the differences across the boundary is clearly observed. Figure 1 (d) shows the profile of the intensity of charge exchange emission from carbon impurity. The intensity of carbon impurity at the center of the plasma decreases as the ion temperature increases, and it becomes one digit smaller than that before the ion temperature rise, while the intensity changes small at the edge as shown in Fig.1 (d). This observation shows that the hollow profile of the carbon density is produced in the high ion temperature plasma with steep gradient of the ion temperature. We denote that the hollow profile observed with the steep gradient of ion temperature as “Impurity Hole”.

3. Impurity hole

3.1. Extremely hollow profile of carbon impurity

The impurity hole is characterized by an extremely hollow profile of impurity observed with the steep gradient of ion temperature in the confinement improved mode. There is a discharge in which the impurity hole is clearly observed [3]. A plasma with steep ion temperature gradient in the discharge is produced with injection of a cylindrical carbon pellet into the plasma with B=2.676T, R_{ax}=3.6m, γ=1.254, and B_q=100%. The plasma is sustained with the N-NBI. The P-NBI is modulated on and off with 5 Hz as a probe beam for the charge exchange spectroscopy. The P-NBI also contributes to the ion heating. An extremely hollow profile of the carbon density is observed in the decay phase after the carbon pellet injection while the ion temperature gradient increases due to both the increase of the deposition power and the improvement of the ion transport. Figures 2 (a)-(d) show the time evolutions of the carbon density, electron density, the gradient of ion temperature and the gradient of electron temperature, respectively. The carbon pellet is injected at t=0.8s and the size of the carbon pellet is ϕ1.4 mm x 1.4mm. The carbon and electron density is increased with the carbon pellet injection and then the densities decrease, while the hydrogen particles are supplied with only the neutral beams. The decay speed of the carbon density at the edge is comparable to the decay speed of the electron density. The decay speed of the carbon density near the plasma center is faster than that at the edge. The gradient of ion temperature increases and reaches 10keV/m, while the gradient of the electron temperature is weak (~3 keV/m) during the decay phase of the electron density. The density of the carbon near the center is smaller than that at the edge at earlier time of the discharge. The density of the carbon near the center becomes larger than that at the edge after the ion temperature gradient becomes large. This observation suggests that the ion temperature gradient plays an important role of the impurity transport which enhances the decay speed of the carbon near the plasma center. Figures 2 (e)-(h) show the radial profiles of the carbon density and electron density before and after the ion temperature gradient rise. The profile of the carbon is peaked at the plasma center just after the carbon pellet injection and becomes extremely hollow in the time scale of a few hundred milliseconds during the decay phase. On the contrary, the electron density profile stays peaked and does not become hollow. This observation indicates that the bulk ion profile is always peaked during the decay phase because of the fueling of the neutral beams. The central carbon density drops to $0.2\text{x}10^{17}\text{m}^{-3}$, which is only 0.3% of the central electron density at t=1.65s. It should be noted that the hollow profile of the carbon density is due to the faster decay of the carbon density near the center than that at the edge and not due to the increase of the influx.

The transport analysis has been performed with the time slices of the carbon in the discharge. It is well known that there is a significant contribution by off-diagonal terms of the transport matrix in the particle transport, and the radial particle flux Γ normalized by the density can be written with a sum of diffusive (diagonal) terms and non-diffusive (off-diagonal) terms as

$$\frac{\Gamma}{n} = -D\frac{1}{n}\frac{\partial n}{\partial r} + V \,, \tag{1}$$

where n is the density of the ions, D is the diffusion coefficient, and V is the convection velocity driven by the gradient of other parameters. The radial particle fluxes of carbon and proton and the density gradients of carbon and proton are calculated from the time slices of the carbon and proton density profiles which are obtained experimentally. The radial profiles of the particle source due to the beam fueling are calculated using the FIT code based on the measured temperature and density profiles. The transport analysis has shown that the extremely hollow profile of carbon is attributed to the large positive convection velocity and small diffusion coefficient in the plasma core. The dependence of the convection velocity of carbon on the gradient of T_i suggests that the outward convection of carbon impurity driven by the ion temperature gradient.

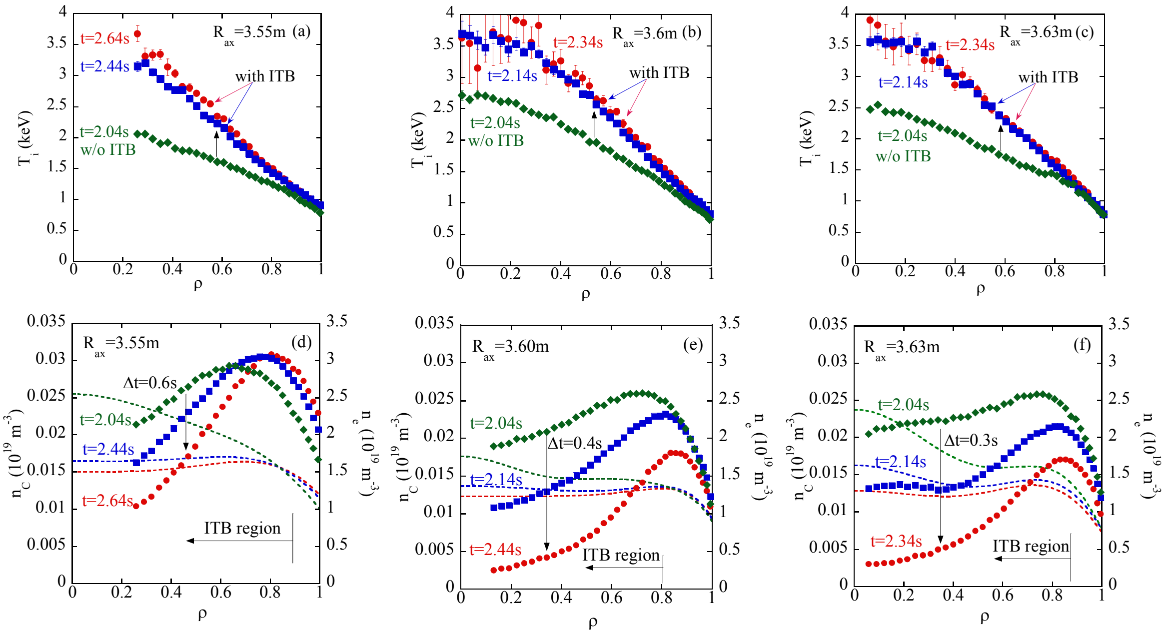

FIG.3. Radial profile of ion temperature in the plasma with (a) Rax=3.55m, (b) 3.6m, and (c) 3.63m. Radial profile of carbon density in the plasma with (d) Rax=3.55m, (e) 3.6m, and (f) 3.63m. Dashed lines in (d)-(f) shows the fitted line of electron density profile.

3.2. Dependence on the position of magnetic axis

Radial position of the magnetic axis, R_{ax}, is one of the important parameters, which changes the helical ripples and affects to behaviours of helical plasmas. It has been known that the change of the magnetic axis position affects not only the neoclassical transport but also the anomalous transport. There is a simulation result which shows turbulent transport is reduced with enhancing zonal-flow generation in the plasma with inward shifted configuration [4]. Thus it is important to investigate the dependence of various phenomena in helical plasmas on the magnetic axis position. We have investigated the dependence of the impurity hole on the magnetic axis position in high ion temperature discharges. Figures 3 (a)-(c) show the radial profiles of ion temperature in the case of R_{ax}=3.55m (inward shifted configuration), 3.6m and 3.63m (outward shifted configuration), respectively. The strength of the magnetic field are 2.789T, 2.75T, and 2.727T for R_{ax}=3.55m, 3.6m, and 3.63m, respectively. There are no significant differences in the ion temperature profile and the gradient. The ion temperature gradient is 4.5keV/m with the ITB and it is 2keV/m without the ITB at ρ=0.5 in these plasmas. Figure 3 (d)-(f) show the radial profile of carbon and electron density in the discharges with and without the ion ITB. Development of hollow profile of carbon (impurity hole) is observed associated with the increase of ion temperature gradient due to the ion ITB. The fit curves of the measured electron density are also plotted with dashed line and it kept peaked or flat during the discharges. The depth and width of the hollowed carbon profiles becomes deeper and wider in the plasma with outward shifted configuration than in the plasma with the inward shifted configuration. The differences in impurity holes are also observed in the time evolution of the carbon density profiles. The time Δt in Fig.3 (d)-(f) is the time until the end of the profile changes. The Δt is smaller in the plasma with outer shifted configuration than that in the plasma with inner shifted configuration. The hollow profile is always inside the ITB region in these discharges because the steep gradient of ion temperature is inside the ITB region.

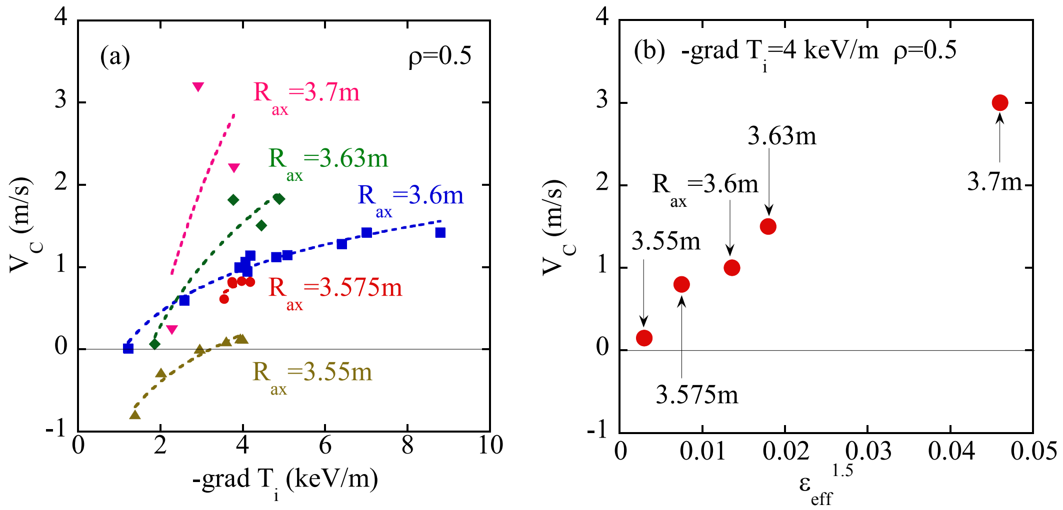

FIG.4. (a) Dependences of convection velocity of carbon on the ion temperature gradient in the plasma with different magnetic axis position. (b) The convection velocity when the ion temperature gradient is -4keV/m plotted as the function of effective ripple strength.

Figure 4 (a) shows the dependences of convection velocities of carbon on the ion temperature gradient for the various magnetic axis positions at ρ=0.5 where the convection velocity become large. Change of the convection velocity is more sensitive to change of the ion temperature gradient in the plasma with outward shifted configuration than that in the plasma with inward shifted configuration. This result suggests that the impurity hole becomes strong as the magnetic axis is shifted outward inside the ITB region where the ion temperature gradient becomes large. Figure 4 (b) shows the convection velocity at the ion temperature gradient of -4keV/m plotted as the function of the strength of the helical ripple effect which can be changed with the magnetic axis position. The outward convection (positive sign) increases associated with the increasing the effect of ripples. Thus the clear dependence of the impurity hole on the magnetic axis position is observed.

3.3. Dependence on charge number of impurities

It is expected that the impurity hole depends on the charge number, *Z*, by assuming that the radial electric field connects to the outward convection of impurity transport which produces the impurity hole. The density profiles of helium (*Z*=2, λ=468.6nm), carbon (*Z*=6, λ=529.05nm), and neon (*Z*=10, λ=524.9nm) is measured with charge exchange spectroscopy in high ion temperature discharge. The plasma is produced with magnetic field strength of -2.85T and magnetic axis position of 3.6m The carbon impurity is supplied with a carbon pellet injection at *t*=3.85s. The helium and the neon are supplied by the gas puffing before the CXS measurement. Figure 5 (a) shows the radial profiles of the ion temperature and fit curve of the electron density at *t*=4.07s and 4.37s. The ion temperature is already increased up to larger than the electron temperature at the plasma centre at *t*=4.07 and kept the profile during few hundred milliseconds. The profile of the impurities at earlier time and at later time are shown in Fig.5 (b) and (c), respectively. It is clearly shown that the profiles of impurities become hollowed. The hollow profile of carbon and neon become deeper near the plasma centre. In order to clarify the difference of the hollowness between three impurity profiles, the normalized gradient of density is evaluated. Figure 6 shows the radial profiles of the normalized gradient of density of helium, carbon, and neon before and after the impurity hole developed in the plasma with the ion ITB. The ion temperature and the gradient are achieved

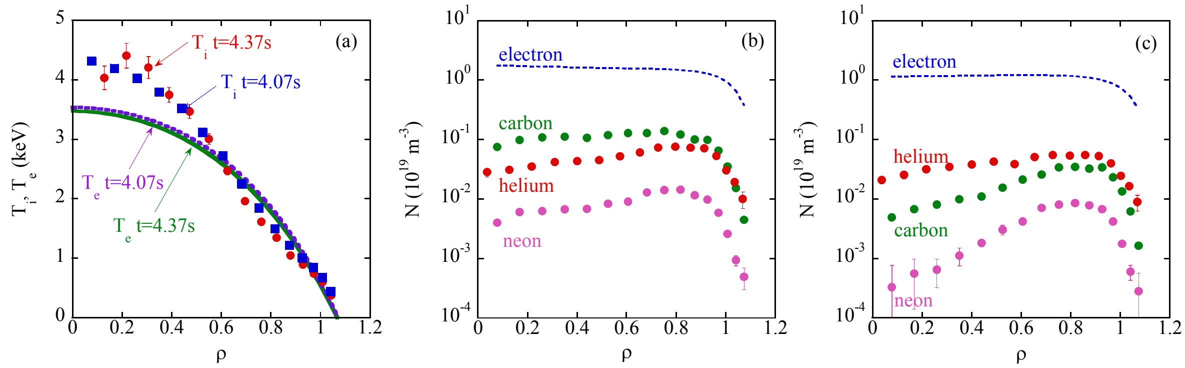

FIG.5. (a) Radial profiles of ion temperature and electron temperature. Radial profiles of electron, helium, carbon, and neon density (b) before and (c) after the impurity hole developed.

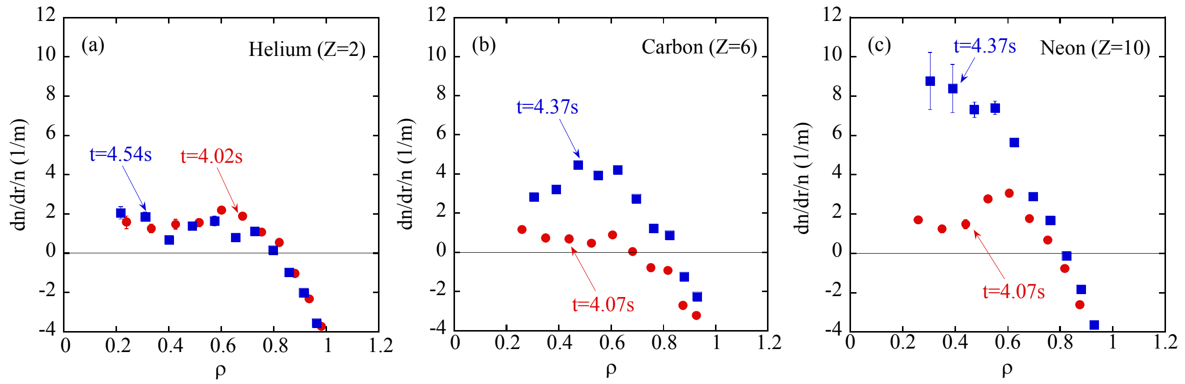

FIG.6. Radial profiles of normalized density gradient of (a) helium, (b) carbon, and (c) neon profile before and after the impurity hole developed.

4. Discussion

The mechanism of the impurity hole is still an open question. The neoclassical transport is a first candidate for the dominant player on the impurity hole. The plasmas in which observed the impurity hole is in low collisionality region due to high ion and electron temperature and low density. Neoclassical prediction and measurement with heavy ion beam prove show the negative radial electric field near the plasma centre [5]. Neoclassical prediction with GSRAKE code [6], which can calculates particle transport in stellarator, shows the inward convection of impurity due to the negative radial electric filed near the plasma center. The predicted inward convection is opposite to the observed impurity convection which directs outward [3]. It should be noted that the predicted particle flux lacks the contributions of the momentum transfer between the bulk ion and impurities. This contribution yields a trend that impurity profile can be more peaked with peaked density profile of bulk ion, and more hollowed with peaked temperature profile of bulk ion [1]. The contribution due to the temperature gradient is well known as the “temperature screening”. The observed outward convection of impurity increases associated with the increase of ion temperature gradient. Although the contribution is seemingly dominant to the outward convection of impurities, the contribution can not be explained the clear dependence on the magnetic axis position. Furthermore a non-linear phenomena that the carbon density suddenly decrease after the ion temperature gradient reaches a critical value while the carbon density increased just before the critical value has been observed in the impurity hole[7]. Thus the observations of the impurity hole can not be explained uniformly from a viewpoint only with the neoclassical transport. The turbulence transport therefore can be a next candidate for the dominant player of the impurity transport in the high ion temperature discharges in LHD.

5. Summary

An extremely hollow profile of carbon impurity is observed in the plasma with the steep gradient of the ion temperature. We denoted the hollow profile as "Impurity hole". Large outward convection and small diffusion of the impurity is a key to produce the impurity hole. Dependence of the impurity hole on the magnetic axis position is clearly observed in the plasma with steep gradient of ion temperature. It is suggested that the impurity hole becomes strong as the magnetic axis is shifted outward. Dependence of the impurity hole on the charge number, Z, is also observed. The density profile of higher Z ion species becomes more hollowed. The turbulence transport can be one of candidates for the dominant player of the impurity transport in the high ion temperature discharges in LHD.

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References

[1] WADE, M. R. et al., "Experimental Confirmation of Impurity Convection Driven by the Ion-Temperature Gradient in Toroidal Plasmas" Physical Review Letters **84** (2000) 282.

[2] MCCORMICK, K et al., "New Advanced Operational Regime on the W7-AS Stellarator" Physical Review Letters **89** (2002) 015001.

[3] YOSHINUMA, M. et al., "Observation of an impurity hole in the Large Helical Device", Nuclear Fusion **49** (2009) 062002.

[4] WATANABE, T.-H. et al., "Reduction of Turbulent Transport with Zonal Flows Enhanced in Helical Systems" Physical Review Letters **100** (2008)195002.

[5] IDO, T. et al., "Experimental study of radial electric field formation and electrostatic potential fluctuation in the Large Helical Device", in 37th EPS Conference on Plasma Physics (submitted to Plasma Phys. Control. Fusion) (2010).

[6] BEIDLER, C. D. et al., "A general solution of the ripple-averaged kinetic equation (GSRAKE)", Plasma Physics and Controlled Fusion **37** (1995) 463-490.

[7] IDA, K. et al., "Observations of an impurity hole in a plasma with an ion internal transport barrier in the Large Helical Device", Physics of Plasmas **16** (2009) 056111.