Impurity Transport in Reversed Shear and ELMy H-Mode Plasmas of JT-60U

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Abstract

The particle transport for several impurity ion species was investigated in reversed shear and ELMy H-mode plasmas on JT-60U. Particle diffusivity for neon was evaluated from gas-puffing modulation experiments; the diffusivity was smaller by one order of magnitude at the internal transport barrier in reversed shear plasmas than in ELMy H-mode plasmas. An increase of the inward pinch velocity for neon was observed at the internal transport barrier in the reversed shear plasma. The particle transport coefficients at the internal transport barrier were compared for neon, carbon and helium. The particle diffusivity was almost the same for all ions, while the inward pinch velocity was larger for ions having higher charge state.

Keywords:

JT-60U, impurity transport, reversed shear plasma, internal transport barrier, ELMy H-mode plasma, particle diffusivity, convective velocity, gas-puffing modulation experiment, electrical charge dependence

1. Introduction

An improved confinement mode has been found in reversed shear plasmas [1-3] which have a negative magnetic shear region in the plasma center due to a hollow current profile. In reversed shear plasmas, an Internal Transport Barrier (ITB) characterized by steep gradients in the density and temperature profiles was observed near the position where the safety factor (q) has a minimum value. In reversed shear plasmas on JT-60U, an equivalent fusion gain ($Q_{DT}$) of 1.25, which is defined for transient conditions involving the $dW/dt$ term, has been obtained with a W-shaped semi-closed divertor configuration [4]. This gain is larger than the largest value of $Q_{DT}$ = 1.05 so far obtained with an open divertor configuration. The reduction of $Z_{eff}$ from 3.5 to 3.2 largely contributed to the achievement of the higher $Q_{DT}$ value after the divertor modification. However, impurity contamination is still high and must be reduced for efficient operation of fusion reactors. In the ITB region of reversed shear plasmas, the thermal diffusivity was significantly reduced to the same level as the neoclassical prediction [5], while anomalous diffusive transport is dominant in other improved confinement modes such as ELMy H-mode plasmas. High impurity contamination in reversed shear plasmas might reflect the neoclassical nature of the particle transport in these plasmas, because neoclassical theory predicts that higher charge state (Z) impurities are accumulated in the plasma center [6,7]. In order to investigate the compatibility of the reversed shear plasma with requirements for fusion reactors, understanding of the particle transport characteristics is important. Therefore, it is useful to evaluate the particle diffusivity and the convective velocity for different impurity species with different charge states and to compare them in the neoclassical-transport-dominated
and the anomalous-transport-dominated regions.

So far, the impurity transport has been investigated for various impurity species in many machines. The wide range of impurity behavior has been observed experimentally. Anomalous transport without central impurity accumulation was usually observed in ohmic heated plasma and L-mode plasma with sawtooth activities [8,9]. In the improved confinement mode such as H-mode plasma and counter beam injected plasma, the experimental results consistent with neoclassical transport were observed where impurity is strongly accumulated in the plasma center [10-14]. The impurity behavior has been also investigated from the relation to MHD activities such as ELM and sawtooth [15,16]. The technique for the estimation of impurity transport coefficients has been progressed. The gas-puffing modulation [17], pellet injection [18] and the laser-blow-off [19] techniques were applied for estimation of particle transport coefficients. The investigation of impurity behavior in the ITB region where thermal transport is dominated by the neoclassical transport is located in a new attractive research area.

In JT-60U, the particle diffusivity and convective velocity for helium have been evaluated in reversed shear and ELMy H-mode plasmas based on helium gas-puffing modulation experiments [20-22]. The particle diffusivity in the ITB region of the reversed shear plasma was observed to be much smaller than that in ELMy H-mode plasmas, while the inward pinch velocity remained at the same level. In this paper, the particle diffusivity and convective velocity for neon are evaluated using the same method reported in refs. [20-22] in reversed shear and ELMy H-mode plasmas. Generally, helium and neon gases were regarded to be unsuitable for the modulation experiments due to the high recycling rate. In fact, the helium and neon densities increased with time in the gas-puffing modulation experiments. However, the modulated component was observed in the increasing helium and neon densities, because the recycling rate was reduced by the strong shielding effect in the W-shaped divertor and divertor pumping. Moreover, in order to check validity of the particle transport coefficients evaluated from the modulated impurity density, consistency with the time evolution of the non-modulated density was discussed. Then the particle transport characteristics for different impurity species, helium, carbon and neon, are compared based on the evaluated particle diffusivity and convective velocity. Here, the particle transport coefficients for carbon are evaluated only in the ITB region from the time evolution of the carbon density profile, because the carbon density could not be modulated in gas-puffing modulation experiments using methane (CH₄) gas due to the large back-ground carbon density, since carbon is the main impurity in JT-60U.

The particle transport coefficients for neon are evaluated based on gas-puffing modulation experiments in Sec. 2. The particle transport coefficients for helium and carbon are described in Sec. 3 and Sec. 4, respectively. In Sec. 5, the Z dependence of the particle transport is discussed, followed by a summary in Sec. 6.

2. Neon Transport

2.1 Gas-puffing modulation experiment

The gas-puffing modulation experiments using neon gas were performed in deuterium reversed shear and ELMy H-mode plasmas with a plasma current of Iₚ = 1.0 MA and a toroidal magnetic field strength of Bₗ = 2.1 T. The diagnostics related to this paper are shown in Fig. 1 together with a plasma configuration of a reversed shear plasma and the location of neon gas-puffing. The neon density profile was measured using charge-exchange recombination spectroscopy (CXRS) with a time resolution of 16.7 ms at 20 radial positions. The measuring positions are shown by open circles in Fig. 1. This CXRS system is usually used for ion temperature.

![Fig. 1 Plasma configuration and diagnostic arrangements related to this study. Open circles show the measuring positions of CXRS, and cross symbols show the measuring position of the MSE diagnostic. Dark hatching shows the measuring area of TMS. The gas-puffing position is also shown by light hatching.](image-url)
measurements from the emission spectrum of the carbon impurity. In this experiment, the ion temperature was derived from the emission spectrum of the neon impurity. The profiles of the electron density and temperature were measured with a Thomson scattering system (TMS), and the current profile was derived from the motional Stark effect (MSE) measurements. Neon gas was puffed from the outer baffle plate. The plasma configuration was selected to be a major radius of \( R = 3.4 \) m, a minor radius of \( a = 0.83 \) m and a triangularity of \( \delta = 0.26 \) for the reversed shear plasma and \( R = 3.5 \) m, \( a = 0.85 \) m and \( \delta = 0.3 \) for the ELMy H-mode plasma.

The time evolution of \( I_p \), the NBI input power \((P_{\text{NBI}})\), the line averaged electron density \( (\bar{n}_e)\), the stored energy \( (W)\), the neutron yield rate \( (S_*)\), the \( \Delta \alpha \) emission intensity from the divertor, the neon gas-puffing rate and the fully ionized neon density are shown in Fig. 2. Feedback control of PNBI using the \( S_* \) signal is applied from \( t = 4.6 \) s for suppression of early \( \beta_p \) collapse. The NBI heating power is decreased from 12 MW to 8 MW during \( t = 5.5-6 \) s to allow prolonged sustained of the steady state phase. The neon gas-valve is repetitively opened and closed with a frequency of 1.5 Hz. The values of \( S_* \) and \( W \) slightly increase from \( t = 5.5 \) s until \( t = 6.4 \) s. The value of \( \bar{n}_e \) slightly increases but is not modulated with the neon gas-puffing. In this discharge, ELM activity is observed in the \( \Delta \alpha \) emission intensity. The neon density starts to increase from ~250 ms after the first opening of the neon gas-valve due to a time delay in the gas-feed system, and the modulated neon density is observed. For the ELMy H-mode plasma (see Fig. 2 (b)), the NBI input power of 12 MW is applied from \( t = 6.5 \) s. The value of \( \bar{n}_e \) slightly increases during \( t = 7-8.2 \) s, and the values of \( W \) and \( S_* \) remain almost constant during \( t = 7-8.2 \) s. The values of \( \bar{n}_e \), \( W \) and \( S_* \) decrease at \( t = 8.2 \) s and then stay almost constant until the end of NBI heating. These degradations are commonly observed in other ELMy H-mode plasmas with neon gas-puffing and might be related to the penetration of the neon impurity into the core region. Strong ELM activity is observed in the \( \Delta \alpha \) emission intensity during \( t = 7-8.5 \) s, but it gradually decreases after \( t = 8.5 \) s. In this discharge, sawtooth activity is also observed with an inversion radius of about \( r/a = 0.25-0.3 \). The neon density starts to increase with a 250 ms delay from the onset of neon gas-puffing and weakly modulated at the gas-puffing modulation.
frequency of 2 Hz.

The electron density profile measured using the Thomson scattering system and the \( q \) profile for the reversed shear (\( t = 6.0 \) s) and ELMy H-mode (\( t = 7.0 \) s) plasmas are shown in Fig 3 (a) and (b), respectively. The \( q \) profile for the reversed shear plasma is derived from the MSE measurement, and that for the ELMy H-mode plasma is derived from the equilibrium calculation. In the reversed shear plasma, a steep density gradient is observed around \( r/a = 0.3-0.4 \), indicating the formation of an Internal Transport Barrier (ITB), while in the ELMy H-mode plasma the density gradient is small everywhere in the core region. In the reversed shear plasma, the \( q \) minimum value is estimated to be about 2.1 and is located at \( r/a = 0.5 \). Negative magnetic shear is produced in the region of \( r/a < 0.5 \), and an ITB is formed inside the position of the \( q \) minimum value. The \( q \) profile for the ELMy H-mode plasma increases monotonically with radius, and the central \( q \) value is less than 1. The H-factor (enhancement factor over the ITER89-P scaling law [23]) is estimated to be 1.4 and 1.6 for the reversed shear (\( t = 6.0 \) s) and ELMy H-mode (\( t = 7.0 \) s) plasmas, respectively.

Figure 4 shows the neon density profiles at 0.6 s after the start of the neon gas-puffing for the reversed shear (\( t = 5.6 \) s) and ELMy H-mode (\( t = 7.6 \) s) plasmas. For the reversed shear plasma, an ITB in the neon density is also observed around \( r/a = 0.3-0.4 \) similar to the electron density ITB location. The neon density has a peak value around \( r/a = 0.2 \), and decreases toward the plasma center. For the ELMy H-mode plasma, the neon density has a peak value around \( r/a = 0.4-0.5 \), and also
decreases toward the plasma center.

### 2.2 Methods of analysis and transport simulation

The particle continuity equation for the impurity ion can be represented as follows:

\[
\frac{\partial n_i}{\partial t} = - \nabla \cdot \mathbf{J}_i + s_i, \quad (1)
\]

where \( n_i \) is the impurity density, \( \mathbf{J}_i \) is the impurity flux across the magnetic field and \( s_i \) is the impurity source density. We can define a particle diffusivity \( D \) and a convective velocity \( v \) by assuming the impurity flux to be expressed as a sum of the diffusion term and the convective term as follows:

\[
\mathbf{J}_i = -D \nabla n_i + v \cdot n_i. \quad (2)
\]

When we express the modulated impurity density \( \tilde{n}_i \) as follows:

\[
\tilde{n}_i = A(r) \cdot \sin (\omega \cdot t - \phi(r)), \quad (3)
\]

the time independent solution of \( D \) and \( v \) can be obtained as follows [20]:

\[
D = -\omega \cdot (Y \cdot \sin \phi + X \cdot \cos \phi) / \frac{\partial \phi}{\partial r} A, \quad (4)
\]

\[
v = -\omega \left[ \frac{\partial A \cdot Y \cdot \frac{\partial \phi}{\partial r} \cdot A \cdot X}{\partial r} \sin \phi + \left( \frac{\partial \phi}{\partial r} A \frac{\partial A}{\partial r} X \right) \cos \phi \right] / \frac{\partial \phi}{\partial r} A, \quad (5)
\]

where

\[
X = \int_0^r r \cdot A \cdot \cos \phi \, dr, \quad Y = \int_0^r r \cdot A \cdot \sin \phi \, dr,
\]

in the region where \( s_i \) can be neglected. Since the neon was fuelled by gas-puffing, there is no source in the plasma center where the density is determined by particle transport from the edge region. Therefore, the particle transport coefficients can be uniquely obtained from the amplitude and phase of the modulated component in the plasma center. In this analysis, only the modulated component is used, and the evaluation is limited to the plasma center where there is no source. Therefore, estimation of the time evolution of the recycling neon source is not required for the evaluation of \( D \) and \( v \), although the neon density increased due to the recycling neon source as shown in Fig. 2. If the recycling neon source is quantitatively estimated, \( D \) and \( v \) can be evaluated in the whole plasma region. For estimation of the recycling neon source, the 2-D neon behavior in the divertor region must be considered where the impurity transport is determined by not only perpendicular forces but also parallel forces such as friction and the thermal gradient force. However, the impurity transport in the divertor region is not completely understood at present. Furthermore, the absolute values of the amplitude and phase are not required in this analysis. Only the relative change of the amplitude and phase are required.

The helium transport was analyzed in ref. [24] for the reversed shear plasma of JT-60U based on the time response of the helium density profile to a short helium gas puff. In the analysis method used in ref. [24], the background helium ion density and the uncertainty in the source term affect the analysis results. The perturbation technique used in this paper has the advantages that the background ion density and the recycling source do not affect the analysis, and also a unique solution of the particle transport coefficients is obtained from the amplitude and phase profiles of the modulated impurity ion density. A similar technique was used in TFTR [25,26], but their analysis was based on the density build-up after a single pulsed gas puff.

In order to investigate the penetration depth of the neon fuelled by gas-puffing, a simulation of the neon transport has been carried out, in which only the ionization process is included. The recombination and charge exchange reaction rates are sufficiently smaller than the ionization reaction rate for the JT-60U plasma parameters. The particle continuity equation for the \( j \)-th ionized neon ions can be represented as follows:

\[
\frac{\partial n_j}{\partial t} = - \nabla \cdot \mathbf{J}_j + n_e n_{j-1} < \sigma v >_{\text{ionization}} \quad \quad (6)
\]

\[
-n_e n_j < \sigma v >_{\text{ionization}} \quad \quad (7)
\]

where \( n_j \) is the ion density of the \( j \)-th charge state and \( < \sigma v >_{\text{ionization}} \) is the ionization rate of the \( j \)-th charge state ion.

First, the equilibrium density profile was calculated for all ion charge states. Figure 5 shows the calculated neon density profiles for atomic (Ne\(^0\)) and ions (Ne\(^{+1}\), Ne\(^{+2}\), Ne\(^{+3}\), Ne\(^{+4}\) and Ne\(^{+9}\)). In this calculation, the central electron density and temperature were assumed to be \( 2.4 \times 10^{19} \text{ m}^{-3} \) and 3.8 keV, respectively, which are typical values in the ELMy H-mode plasmas of JT-60U. The value of \( D \) was assumed to be a constant value.
of 2 m²/s and the particle pinch velocity \( v \) to be a function of radius as \( v(r/a) = -10(r/a)^3 \) m/s. These values are estimated based on the particle coefficients for helium ions previously obtained in ELMy H-mode plasmas [21,22]. The neon density penetrates into the main plasma as the charge state becomes high. The density profile of Ne\(^{9+} \), which is the source for the fully ionized neon (Ne\(^{10+} \)), has a peak value around \( r/a = 0.80-0.85 \) and disappears inside of \( r/a = 0.4-0.5 \). The density profile of Ne\(^{10+} \) is almost flat within \( r/a = 0-0.6 \) and monotonically decreases toward the edge.

Next, the response of the Ne\(^{10+} \) density to the modulated source term with a sine function was calculated. In Fig. 6 (a), the calculated amplitude and phase of the modulated Ne\(^{10+} \) density are shown. The amplitude has a flat profile in the region of \( r/a = 0-0.6 \) and decreases toward the plasma edge, as does the equilibrium Ne\(^{10+} \) density profile. The phase has a minimum value at \( r/a = 0.85 \), where the equilibrium Ne\(^{9+} \) density has a maximum value, and the phase increases continuously toward the plasma center. In Figs. 6 (b) and (c), the solid lines show \( D \) and \( v \) profiles, respectively, evaluated from the calculated amplitude and phase of the modulated Ne\(^{10+} \) density shown in Fig. 6 (a) using eqs. (4) and (5) with the assumption that \( s_i \) can be neglected over the whole plasma region. Therefore, in the region where the particle transport is dominant, the calculated \( D \) and \( v \) agree with the assumed \( D \) and \( v \), while in the edge region where the density is determined by not only transport but also the source, the calculated \( D \) and \( v \) disagree with the assumed \( D \) and \( v \). The values of \( D \) and \( v \) assumed in the

modulated Ne\(^{10+} \) density calculation are also shown by the dotted lines in Figs. 6 (b) and (c), respectively. Although there is some scatter in the \( D \) profile due to the calculation accuracy, the calculated \( D \) and \( v \) are almost the same as those assumed in the calculation in the region of \( r/a < 0.5 \). However, in the region of \( r/a > 0.5 \), the calculated \( D \) and \( v \) are quite different from the assumed \( D \) and \( v \). It can be concluded from these figures that \( D \) and \( v \) can be evaluated without the consideration of source term effects in the region of \( r/a < 0.5 \). The penetration depth of the source depends on the edge transport coefficients and does not depend on the central...
transport coefficients. The penetration depth of the source increases with $D$ and the inward pinch velocity. In the range of $D = 1-2$ m$^2$/s and $v(a) = -10 \sim -20$ m/s, the source penetration is negligible in the region $r/a < 0.5$.

2.3 Results of analysis

In order to express the modulated neon densities measured by CXRS as eq. (3), we fitted the measurements using a sum of sine and polynomial functions by the least squares fit method. The sine function expresses the modulated component and the polynomial function expresses the time evolution of the non-modulated component. Figure 7 shows the measurements and the fitted curves at several radial positions for the (a) reversed shear and (b) ELMy H-mode plasmas. The data during $t = 5.4-6.4$ s were used for the reversed shear plasma and the data during the early gas-puffing phase of $t = 7.4-8.2$ s were used for the ELMy H-mode plasma. The modulated component is clearly observed for both discharges, and the curves fit the measurements well. The dashed lines show the timing where the modulated component becomes zero. It can be seen from these figures that the phase of the modulated component is delayed toward the plasma center.

In Figs. 8 (a) and (b), the amplitude and phase of the modulated neon density are plotted, respectively, in the region of $r/a = 0-0.6$. The error bar in these figures is ascribed to uncertainties in the fitting process as described above. The amplitude for the reversed shear plasma is almost the same as that for the ELMy H-mode plasma in the region outside the ITB. However, the amplitude for the reversed shear plasma significantly changes in the ITB region, and is larger than that for the ELMy H-mode plasma in the region inside the ITB. For the ELMy H-mode plasma, the amplitude continuously changes and decreases toward the plasma center in the region $r/a < 0.35$. The phase also changes continuously for the ELMy H-mode plasma. In contrast, the phase significantly changes at the ITB region for the reversed shear plasma. Basically, the amplitude tends to depend on $v$ and the phase tends to depend on $D$. The increase of the amplitude toward the plasma center in the ITB

![Graphs showing modulated neon densities](image)
region of the reversed shear plasma essentially indicates a large inward pinch velocity, and the large change of the phase in the ITB region of the reversed shear plasma indicates a small value of $D$. In this analysis, a sum of sine and polynomial functions was used for the fitting to the measurement as mentioned above. If we use a sum of sine and linear functions, the data scatter shown in Fig. 8 becomes large but the global features are not changed.

The particle diffusivity and convective velocity evaluated from the amplitude and phase of the modulated component are shown in Figs. 9 (a) and (b), respectively. Here, the profiles of the amplitude and phase of the modulated neon density shown by the solid and dotted lines in Fig. 8 are used. In Fig. 9 (b), a positive convective velocity corresponds to the outward direction and a negative convective velocity corresponds to the inward direction. In order to determine the errors in $D$ and $v$, the following calculation was performed. First, the errors of the amplitude and phase were calculated using a random number with a normal distribution chosen to reflect the fitting error shown in Fig. 8 and the measurement error. Next, $D$ and $v$ were evaluated assuming the above error for many cases, and the distribution of $D$ and $v$ was obtained. Finally, the error was determined for the central part in which 70% of all the data was included. The value of 70% corresponds to the probability that the normally distributed data covers a range of $1\sigma$.

The particle diffusivity is in the range 0.1–2 m$^2$/s for the reversed shear plasma and 0.4–2 m$^2$/s for the ELMy H-mode plasma, respectively. It can be seen from Fig. 9 (a) that $D$ is reduced in the reversed shear plasma by an order of magnitude in the ITB region compared with that in the inside and outside regions. The value of $D$ for the ELMy H-mode is almost the same as that for the reversed shear plasma except in the ITB region. A clear difference in $D$ between the reversed shear and ELMy H-mode plasmas is seen only in the ITB region, and the difference is as large as an order of magnitude.
An inward pinch velocity of about -3 m/s is observed in the ITB region of the reversed shear plasma. Although the error bars of $v$ are large in the region outside the ITB, the inward pinch velocity clearly increases in the ITB region. An outward velocity is observed for the ELMy H-mode plasma in the plasma center region. The value of $v$ for neon is consistent with that for helium reported in refs. [21,22] considering the error bars. One of the candidates for the mechanism responsible for the outward velocity is sawtooth activity [15] as mentioned in refs. [21,22]. However, in this discharge, the sawtooth inversion radius was evaluated to be $r/a = 0.25-0.3$, and an outward velocity is also observed in the region outside the inversion radius. Definitive evidence that the outward velocity can be ascribed to sawtooth activity has not emerged yet, and further work needs to be done.

2.4 Consistency check with non-modulated component

In this section, the consistency of $D$ and $v$ evaluated in the previous section with the non-modulated neon ion density is discussed. The non-modulated component of the neon ion density also has the information of the particle transport as well as the modulated component. It is important for verification of the particle transport coefficients evaluated from the modulated component to confirm whether the non-modulated component can be reproduced using the evaluated particle transport coefficients or not.

Figures 10 (a) and (b) show the comparison of the non-modulated neon ion density profiles between experimental observation and calculation for the reversed shear and ELMy H-mode plasmas, respectively. Here, the particle transport coefficients in the region of $r/a > 0.6$ including the SOL plasma and the time evolution of the source term reproducible the measurement in this region were chosen. The source profile was calculated with an assumption that neon penetrates into the main plasma through the SOL plasma, and neon behavior in the divertor plasma was not considered. For the accurate estimation of the source term, 2-D neon behavior in the divertor region should be taken into account as described in Sec. 2.2. In this calculation, the source profile might be deeply estimated, because ionization of low charge state neon ion in the divertor plasma is not considered. Therefore, in this paper, discussion is limited in the source-free region ($r/a < 0.3$). For the reversed shear plasma, the measured neon ion density (symbols) of the non-modulated component shows flat profile relatively at early phase, and then ITB grows up. The calculation (lines) also shows flat profile at early phase, and then ITB grows up. It can be seen from this figure that the calculation is consistent with the measurement. The neon ion can easily penetrate inside ITB because of the inward pinch velocity, even if $D$ reduces in the ITB region. In the region inside the ITB ($r/a < 0.3$), $D$ and $v$ could be optimized in the range of these error bars for the best fitting. For the ELMy H-mode plasma (Fig. 10 (b)), the calculation well reproduces the measurement. These results indicated that the time evolution of the neon ion density profile can be reproduced using the particle transport coefficients evaluated from the modulated component.

3. Helium Transport

The particle transport coefficients for the helium ion have been evaluated based on the helium gas-puffing modulation experiments in the reversed shear...
and ELMy H-mode plasma in refs. [21,22] with the same plasma parameters used in the neon gas-puffing experiments described in Sec. 2. Here, the results of the helium transport analysis are summarized for the discussion in Sec. 5 where the particle transport for several impurity species is compared. Furthermore, the consistency with the non-modulated component is discussed.

The profiles of the evaluated $D$ and $v$ for helium in the reversed shear plasma are shown in Fig. 11 (a). The value of $D$ for helium was in the range of 0.2--2 m$^2$/s, and was reduced in the reversed shear plasma by a factor of 5--6 in the ITB region compared with that in the inside and outside regions. An inward pinch velocity of $-2 - -1$ m/s was observed for helium in the ITB region. However, an increase of the inward pinch velocity in the ITB region was not observed. In this discharge, the power balance analysis indicated that the thermal diffusivities for both the electrons and ions are comparable to neoclassical predictions in the ITB region. The deuterium particle diffusivity was also predicted to be about 0.3--0.4 m$^2$/s in the ITB region with the assumption that carbon was the dominant impurity. Although the species is different, this prediction is consistent with the estimated helium diffusivity. The profiles of $D$ and $v$ for the ELMy H-mode plasma are shown in Fig. 11 (b). The value of $D$ changed from 0.4 m$^2$/s at $r/a = 0.1$ to 2 m$^2$/s at $r/a = 0.5$ and was almost constant in the region $r/a = 0.5$--0.9. An inward pinch velocity was observed except in the region $r/a = 0.3$--0.45, and the value of the inward pinch velocity for the ELMy H-mode plasma was the same level as that for the reversed shear plasma.

In order to check the consistency with the non-modulated component, the time evolution of the helium density was calculated. Here, the background He II intensity in the CXRS signal was used as the source term. In the reversed shear plasma, the helium density profile was calculated for 3 cases, which are used the evaluated $D$ and $v$ (case 1), the evaluated $D$ and smaller $v$ (case 2) and the evaluated $D$ and the half value of $v$ for case 2 (case 3). Figure 12 (a) shows the comparison between measurements and calculations. The profile of $v$ for 3 cases are also shown in the inset as well as the error bar of the evaluated $v$. The calculation for the case 1 shows more peaked profile compared to the measurement except for the ITB region as described in ref. [22]. The calculation in the case 2 gives an acceptable profile. The value of $v$ for the case 2 is consistent with the evaluated $v$ in the region of ITB and inside ITB considering the error bar. However, $v$ is smaller than the evaluated $v$ in the outer region even if the error bar is considered. For the case 3, the density profile is almost flat except in the ITB region which is consistent with the measurement. In the ITB region, the calculated density gradient is smaller than the measurement. The value of $v$ in the ITB region for the case 3 is smaller than the evaluated $v$, suggesting that the evaluated value in the ITB region is necessary to reproduce the ITB. This result indicated that the evaluated particle coefficients are consistent with the non-modulated component in the ITB region and the region inside the ITB, but not consistent in the region outside the ITB.

Figure 12 (b) shows the comparison between calculation and measurement for helium density profile in the ELMy H-mode plasma. The calculation is consistent with the measurement except in the outer region ($r/a > 0.9$) as well as for the reversed shear plasma. Although the outward velocity might be too large in the region of $r/a = 0.3$--0.4, this could be reduced in the range of its error bar. The disagreement in the outer region for both of reversed shear and ELMy H-mode plasmas might come from the difference between the perturbation and non-perturbation transports in the edge region and/or uncertainty of the source term.
4. Carbon Transport

We have also examined the particle transport for carbon, which is the main impurity in JT-60U. Here, we attempted to evaluate the particle coefficients for carbon from the time evolution of the carbon density profile during the high power NBI heating phase without CH₄ gas-puffing, because modulation of the carbon density was not observed in the CH₄ gas-puffing modulation experiment due to the large background carbon density.

In order to evaluate the particle transport coefficients from the time evolution of the density profile, a large change of the density profile is necessary. In the reversed shear plasma, a change of the carbon density profile is observed in the ITB region as the ITB grows. However, the carbon density profile is not significantly changed in the ELMy H-mode plasma. Therefore, the evaluation was limited only in the ITB region of the reversed shear plasma. We analyzed carbon transport in the same discharge used for the helium transport analysis, whose operational conditions are the same as those in the neon gas-puffing modulation experiment shown in Fig. 2 (a). In this discharge, an ITB was observed in the electron density profile in the region of \( r/a = 0.4-0.5 \), and the H-factor (enhancement factor over the ITER89-P scaling law) was estimated to be 1.9.

Figure 13 shows the time evolution of the carbon density \( n_{\text{c}6+} \) profile. The value of \( n_{\text{c}6+} \) increases with radius in the region of \( r/a = 0-0.2 \), and has a flat profile in the region of \( r/a = 0.2-0.46 \). In the region outside the ITB, \( n_{\text{c}6+} \) has a flat profile.

The carbon flux across the magnetic field \( (\Gamma_{\text{c}}) \) was evaluated from the time evolution of the carbon density profile from eq. (1) in the ITB region. Eq. (2) can be rewritten as \( \Gamma_{\text{c}}/n_{\text{c}} = -D\nabla n_{\text{c}}/n_{\text{c}} + v \), which means that a straight line fitted to the data plots of \( \Gamma_{\text{c}}/n_{\text{c}} \) against \( -\nabla n_{\text{c}}/n_{\text{c}} \) based on the data-set with the same values of \( D \).
and \( v \) gives \( D \) from its gradient and \( v \) from its \( y \)-intercept. Generally, the values of \( D \) and \( v \) have been evaluated from the data plots at the same radial position at different times \([27,28]\), because the values of \( D \) and \( v \) are not spatially constant. Figure 14 shows a plot of \( \Gamma_c/n_c \) as a function of \(-V_{n_c}/n_c\) at the ITB position of \( r/a = 0.46 \) during \( t = 5.0-5.18 \text{ s} \). The line fitted to these data plots shown by the solid line in Fig. 14 gives \( D = 0.14 \text{ m}^2/\text{s} \) and \( v = -2.4 \text{ m/s} \). The errors in \( D \) and \( v \) were evaluated to be \( 0.1-0.3 \text{ m}^2/\text{s} \) and \(-1.9 - -3.0 \text{ m/s} \), respectively, from the dotted lines shown in Fig. 14.

The same method was applied during the neon density build up phase in the neon gas-puffing modulation experiments for the ELMy H-mode plasma, in order to check the analysis consistency between the gas-puffing modulation experiment and the analysis method used in this section. Basically, the values of \( D \) and \( v \) evaluated by these methods were the same, because these methods are based on the same transport phenomena. The values of \( D \) and \( v \) were estimated to be \( 0.6-2 \text{ m}^2/\text{s} \) and \( 1.5 - -2 \text{ m/s} \) in the region of \( r/a = 0.2-0.6 \), respectively, which agree within the error bars with those estimated based on the gas-puffing modulation experiment.

In the reversed shear plasma, the values of \( D \) and \( v \) can be estimated only at the ITB region, which were estimated to be about \( 0.3 \text{ m}^2/\text{s} \) and \(-3.5 \text{ m/s} \), respectively. These values are almost the same as the values estimated from the gas-puffing modulation experiment.

In order to check the consistency with the time evolution of the carbon density, the calculation and measurement were compared as shown in Fig. 15. In this calculation, the values of \( D \) and \( v \) evaluated above were used in the ITB region. In the other region, values for neon ions evaluated in Sec. 2.3 were used. The source term was estimated based on the emission from the carbon in the divertor region. In order to reproduce the density profile, the different profile of \( v \) was used in the region of \( r/a = 0.3-0.45 \) before and after \( t = 5.0 \text{ s} \) as shown in the inset. In this discharge, the high power NBI heating was applied from \( t = 5.0 \text{ s} \), and the strong ITB was produced after \( t = 5.0 \text{ s} \). The change of \( v \) could be associated the change of heating power. The calculation well reproduces the measurement except for the central region \((r/a < 0.2)\). The values of \( D \) and \( v \) evaluated above are consistent with the time evolution of the carbon density.

5. Discussion

In this section, we discuss the electrical charge \((Z)\)
dependence of the particle transport based on the transport for helium, carbon and neon. The values of $D$ and $v$ evaluated for the reversed shear and ELMy H-mode plasmas are summarized in Table 1. In the reversed shear plasma, the values of $D$ and $v$ in the ITB region are listed. In the ELMy H-mode plasma, the values of $D$ and $v$ around $r/a = 0.5$ are listed. In the reversed shear plasma, $D$ was almost the same value for helium, carbon and neon. In contrast, the inward pinch velocity seems to be large for high Z species in the ITB region of the reversed shear plasma. In Fig. 16, the inward pinch velocities are plotted as a function of Z. Here, an inward pinch velocity is taken as a positive velocity. It can be seen from Fig. 16 that the absolute value of the inward pinch velocity is almost proportional to the square of Z. Since neoclassical theory predicts that the inward pinch velocity becomes larger as Z becomes higher, the results obtained here are qualitatively consistent with neoclassical theory. These results suggest that since the impurity transport in the ITB region is dominated by neoclassical transport, the high Z impurity is accumulated in the plasma center. A quantitative comparison between the experimental observations and neoclassical predictions should be made in future work based on a multi-species model. In TFTR, the particle transport was analyzed for tritium, helium and carbon [26], and an inward pinch velocity was observed for carbon transport in the enhanced reversed shear plasma, but the inward pinch velocity was negligible for tritium and helium. The tendency that the inward pinch velocity is larger for higher Z is consistent with the results obtained in this paper. A large inward pinch velocity of $-4 \, \text{m/s}$ for carbon was also observed at the ITB region in the optimized shear plasma of JET [29]. In JET, nickel (Ni) transport was also examined in the optimized shear plasma, but a large inward pinch velocity was not observed in the ITB region. In JT-60U, strong emission intensity from highly ionized iron (Fe) ions was observed in the reversed shear plasma in the experimental series analyzed here when the distance from the first wall to the plasma was small with an inward shifted plasma configuration. This observation might indicate accumulation of Fe ions and might be associated with a large inward pinch velocity. Particle transport for heavy metal ions in JT-60U is interesting from the point of view of comparison between experimental observations and neoclassical predictions, and should be investigated in future work. On the other hand, in the ELMy H-mode plasma, $D$ is also the same for helium and neon. Although the error bar of $v$ is large, an increase of the inward pinch velocity for high Z ions is not observed. These results suggest that the impurity transport is different between the ITB region for reversed shear plasmas and the anomalous diffusivity region for H-mode plasmas with ELMs and sawteeth. These experimental results clearly show that suppression of impurity generation and penetration into the main plasma is strictly required if reversed shear plasmas with an ITB are to be used in tokamak fusion reactors.

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Reversed shear plasma (in the ITB region)</th>
<th>ELMy H-mode plasma (at $r/a=0.5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D , [, \text{m}^2/\text{s}]$</td>
<td>$v , [, \text{m/s}]$</td>
</tr>
<tr>
<td>He</td>
<td>0.2-0.3</td>
<td>-1.8-0.86</td>
</tr>
<tr>
<td>C</td>
<td>0.1-0.3</td>
<td>-3.0-1.9</td>
</tr>
<tr>
<td>Ne</td>
<td>0.1-0.2</td>
<td>-4.4-2.3</td>
</tr>
</tbody>
</table>

![Inward pinch velocity as a function of Z in the ITB region of reversed shear plasma. An inward velocity is taken as a positive value.](image)

Fig. 16 Inward pinch velocity as a function of Z in the ITB region of reversed shear plasma. An inward velocity is taken as a positive value.

### 6. Summary

The particle transport for several impurity species was analyzed in reversed shear and ELMy H-mode plasmas. Based on gas-puffing modulation experiments,
the particle diffusivity for neon was evaluated to be $0.1$–$2 \, \text{m}^2/\text{s}$ in the reversed shear plasma and $0.4$–$2 \, \text{m}^2/\text{s}$ for the ELMy H-mode plasma, respectively. The particle diffusivity was reduced in the ITB region of the reversed shear plasma by an order of magnitude compared with that in the regions inside and outside the ITB. The particle diffusivity was also reduced in the ITB region of the reversed shear plasma by an order of magnitude compared with that of the ELMy H-mode plasma. An inward pinch velocity of $-4.4$ – $-2.3 \, \text{m/s}$ was observed in the neon transport at the ITB region of the reversed shear plasma. From the time evolution of the carbon density profile, the particle diffusivity and convective velocity for carbon were also evaluated to be $0.1$–$0.3 \, \text{m}^2/\text{s}$ and $-3.0$ – $-1.9 \, \text{m/s}$, respectively, in the ITB region for the reversed shear plasma. In the ITB region, the particle diffusivity did not depend on the electrical charge, but conversely, the inward pinch velocity increased with the electrical charge. In the ELMy H-mode plasma, $D$ was also the same for helium and neon, and an increase of the inward pinch velocity for high $Z$ ions was not observed. These results suggest that the suppression of impurity generation and penetration into the main plasma is especially important for reversed shear plasmas.

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**References**


