Strong suppression of impurity accumulation in steady-state hydrogen discharges with high power NBI heating on LHD

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Abstract
Strong suppression of impurity accumulation is observed in long pulse hydrogen discharges with high power NBI (neutral beam injection) heating ($P_{\text{nbi}} > 10$ MW) on the large helical device (LHD), even in the impurity accumulation window where the intrinsic impurities such as Fe and C are always accumulated into the plasma core. Density scan experiments in these discharges demonstrate to vanish the window and a new operational regime without impurity accumulation is found in steady state hydrogen discharges. Impurity pinch decreases with increasing ion temperature gradient and carbon Mach number. The peaking of the measured carbon profiles shows strong anti-correlations with the Mach number and its radial gradient. An external torque has a big impact on impurity transport and strong co-current rotation leads to an extremely hollow carbon profile, so-called ‘impurity hole’ observed in high ion temperature modes. Impurity pinch in the plasmas with net zero torque input (balanced NBI injection) is also strongly reduced by increasing ion temperature gradient, which can drive turbulent modes. The combination effect of turbulence and toroidal rotation plays an important role in the impurity transport.

Keywords: impurity transport, steady-state discharge, toroidal rotation

(Some figures may appear in colour only in the online journal)

1. Introduction
Impurity transport study in tokamak and stellarator plasmas has been an issue of concern for several decades. Central accumulation of impurities produces a deleterious combination of fuel dilution and radiation, which strongly limits the possibility of achieving practical fusion energy, and an uncontrolled impurity accumulation may even terminate the fusion plasma. Understanding impurity transport is crucial for sustaining high performance plasmas in magnetic confinement devices.

In heliotrons and stellarators, large superconducting devices such as LHD\textsuperscript{1} and W7-X (Wendelstein7-X)\textsuperscript{2} already comply with long-pulse operation and focus upon the establishment of high performance steady-state plasmas. Significant progress has been already made in sustaining high temperature plasma and maintaining the integrity of the machine for long time in LHD\textsuperscript{3–5}. One-hour discharge with...
the high temperature plasma of 2 keV has been achieved with ICH and ECH heating power of 1.2 MW. The energy injected into the plasma amounts to 3.4 GJ [5]. In steady state operation, one of critical issues is to avoid impurity accumulation, which can lead to early pulse termination by radiation collapse. Long pulse discharges with ICH were usually conducted in the scheme of hydrogen minority heating and helium dominant plasmas were sustained by controlling the minority ratio. Most of long pulse discharges with ICH were terminated by radiation collapse due to the increase of plasma density or the penetration of impurity fluxes into the plasma [6]. However, there has never been an event of long-term impurity accumulation. On the other hand, long pulse hydrogen discharges with NBI heating showed impurity accumulation behavior for high-Z impurities. This notable result might be attributed to the change between helium and hydrogen plasmas, i.e. the difference between helium and hydrogen plasmas, i.e. the high power heating showed impurity accumulation behavior for high-Z impurities. This notable result might be attributed to the difference between helium and hydrogen plasmas, i.e. the high power heating with the high power heating.

**Figure 1.** Typical long pulse discharges with low ($P_{\text{nbi}} = 9.5$ MW) and high power ($P_{\text{nbi}} = 13$ MW) NBI heating. Strong suppression of impurity accumulation is observed in the long pulse discharge with the high power heating.

In this paper, the operational regime in steady-state discharges will be extended to high temperature and high density regions by increasing the NBI heating power and by exploring favorable scenarios capable of preventing impurity accumulation. Impurity behavior in steady state hydrogen discharges with high power heating will be described in section 2, presenting a new operational regime without impurity accumulation. The parameter dependences of carbon density profile will be investigated and the correlation with ion temperature gradient and toroidal rotation will be described. In section 3, the impact of NBI torque input on impurity transport will be investigated and the profile structure of carbon density is compared with that in high ion temperature mode, followed by a description of impurity transport in net zero torque input discharges in section 4. A general discussion and a comprehensive understanding of impurity transport in LHD will be also discussed in section 5.

2. Impurity behavior in steady-state hydrogen discharge

Several specific features of impurity behavior have so far been found in LHD, which has a fully superconducting magnet and generates a heliotron magnetic configuration ($ilm = 2/10$) in steady state for plasma confinement. Steady-state hydrogen transport was obtained from the inter-machine comparison [11]. Recently, studies on impurity shielding criteria for LHD steady-state hydrogen plasmas revealed the important role of radial electric field and the impurity screening effect in the ergodic layer [12]. Theoretical predictions based on neoclassical transport theory for non-axisymmetric configurations underline the importance of the radial electric field. In the standard case with negative radial electric field, the so-called ion-root regime, high-Z impurities are drawn toward the center. Only in the low-density regime it is possible to establish the electron root with positive radial electric field, which flushes out impurities. On the other hand, impurity transport studies in the scrape-off-layer (SOL) region demonstrated a favorable impact on the impurity screening, i.e. the screening of impurity influx from the divertor plates [13, 14]. Impurity transport simulations indicated a clear physical picture of impurity screening in the SOL [15, 16]. The cross-field heat conduction governs the ion energy transport across the islands under high density, low temperature conditions. The friction force dominates over the ion thermal force, dragging impurities outwards. Besides, in short pulse discharges, high confinement plasmas with a high ion temperature at low collisionality indicated an extremely hollow profile of impurity, which is so called ‘impurity hole’ [17–19]. The radial electric field in the core region is weakly negative [20] and a clear physical basis on the strong outward convection has not been found yet. Turbulent transport is another important contribution to impurity transport and might gain increasing importance in impurity transport for tokamak plasmas, but there is no clear evidence in experimental observation and also in theoretical analysis including simulation studies for non-axisymmetric configurations.

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discharges have been produced with a constant heating power and maintained with a constant electron density for more than 5 s. The standard hydrogen discharges have a flat density profile and a peaked temperature profile. Density scans in long pulse discharges showed intrinsic impurity accumulation in a specific density range (plasma collisionality), which is called the ‘impurity accumulation window’. Such an accumulation window has always been found in the density scan for the discharges with NBI heating power of less than 10 MW. Recently, higher NBI heating power (\(P_{nbi} > 10\) MW) has become available for long pulse operation in LHD and impurity behavior in high temperature regime has been investigated in the magnetic configuration with the major radius \(R = 3.6\) m.

### 2.1. Suppression of impurity accumulation in high power NBI discharge

In this experimental series, the combined tangential NBI heating power with co-injection and counter-injection with respect to the direction of toroidal magnetic field (\(B_t = -2.75\) T) is employed. The perpendicular NBI heating power is added to measure the carbon density profile by means of charge exchange spectroscopy (CXS). The carbon density is calculated with neutral beam density attenuating in the plasma, assuming \(Z_{eff} = 2\). Figure 1 shows typical long pulse discharges with different heating power. In the case of low power heating (\(P_{abs} = 9.5\) MW), the central electron temperature \(T_{e0}\) decreases sharply with time. The radiated power density \(S_{rad}\) increases in the core region and the impurity line emission (Fe XXIII) strongly brightens up in the plasma core because of the stainless steel plasma chamber wall. Carbon from the graphite divertor tiles is accumulated in the core plasma. In contrast, all the plasma parameters are maintained almost constant in the high power discharge (\(P_{abs} = 13\) MW) and the amount of intrinsic impurities (Fe, C) in the plasma remains constant during the discharge. The impurity accumulation behavior as seen in the low power case is strongly suppressed. Figure 2 shows the radial profiles of electron temperature, radiated power density and carbon density in the last stage of the discharge \((t ~ 6.5\) s). For the low power discharge, the electron temperature is markedly reduced in the core region. The radiated power increases largely in the core plasma and the radiation profile becomes peaked with time. This remarkable increase in core radiation is caused by intrinsic metallic impurities (mainly iron), thereby resulting in flattening the temperature profile. The carbon density also increases in the core region and a remarkable peaking is observed in the carbon profile. In contrast, a peaked profile of electron temperature is maintained during the discharge in the high power case. The radiation profile with a hollow shape is maintained until the end of the discharge. The increase of core carbon density is stopped at around 1 s after the injection of high power NBI and the carbon profile with a flat shape is maintained during the discharge. Thus, strong suppression of impurity accumulation is found in steady-state hydrogen discharges with NBI heating power higher than 10 MW.

Density scan experiments show that there is no impurity accumulation in the high power discharges. Figure 3 shows the dependence of the increasing rate of core carbon density \((dn_C/dt)\) on background ion collisionality at \(\rho = 0.5\) for different NBI heating power. In the case of low power heating (\(P_{abs} = 9.5\) MW), the core carbon density \((dn_C/dt)\) decreases sharply with time. The radiated power density \(S_{rad}\) increases in the core region and the impurity line emission (Fe XXIII) strongly brightens up in the plasma core because of the stainless steel plasma chamber wall. Carbon from the graphite divertor tiles is accumulated in the core plasma. In contrast, all the plasma parameters are maintained almost constant in the high power discharge (\(P_{abs} = 13\) MW) and the amount of intrinsic impurities (Fe, C) in the plasma remains constant during the discharge. The impurity accumulation behavior as seen in the low power case is strongly suppressed. Figure 2 shows the radial profiles of electron temperature, radiated power density and carbon density in the last stage of the discharge \((t ~ 6.5\) s). For the low power discharge, the electron temperature is markedly reduced in the core region. The radiated power increases largely in the core plasma and the radiation profile becomes peaked with time. This remarkable increase in core radiation is caused by intrinsic metallic impurities (mainly iron), thereby resulting in flattening the temperature profile. The carbon density also increases in the core region and a remarkable peaking is observed in the carbon profile. In contrast, a peaked profile of electron temperature is maintained during the discharge in the high power case. The radiation profile with a hollow shape is maintained until the end of the discharge. The increase of core carbon density is stopped at around 1 s after the injection of high power NBI and the carbon profile with a flat shape is maintained during the discharge. Thus, strong suppression of impurity accumulation is found in steady-state hydrogen discharges with NBI heating power higher than 10 MW.

Density scan experiments show that there is no impurity accumulation in the high power discharges. Figure 3 shows the dependence of the increasing rate of core carbon density \((dn_C/dt)\) on background ion collisionality. In the case of low power heating (\(P_{abs} = 7.5\) MW), the core carbon density remarkably increases with time in a specific collisionality region (impurity accumulation window) as observed before. However, in the discharges with high power heating (\(P_{abs} = 13\) MW), the core carbon density remains almost constant during the discharge and impurity accumulation behavior does not appear in the overall collisionality range. This means that a new operational

![Figure 2](image-url)  
**Figure 2.** Radiation profiles of (a) electron temperature, (b) radiated power density and (c) carbon density at \(t = 6.5\) s in the discharges with different heating power of 9.5 and 13 MW.

![Figure 3](image-url)  
**Figure 3.** Dependence of core carbon density increasing rate on background ion collisionality at \(\rho = 0.5\) for different NBI heating power. The impurity accumulation window observed in the low power operational regime disappears in the high power discharges.
regime without impurity accumulation is found in steady state hydrogen discharges on LHD.

2.2. Mapping of impurity behavior on n-T space

Impurity behavior in long pulse hydrogen discharges with NBI heating can be classified with the plasma parameters (n, T: electron density and temperature) at the plasma edge as shown in figure 4. This mapping is made for standard hydrogen plasmas with gas puffing in the magnetic configuration with R = 3.6 m. In these discharges, the profile structures in density and temperature (flat density and peaked temperature) are kept for scanning the density and heating power. The degree of turbulence increases when the heating power density (plasma pressure) is increased. The evaluation criterion for impurity accumulation is based on the increase of core radiation (dSrad/dt > 0). There is no significant change of core radiation (dSrad/dt ~ 0) in the discharges without impurity accumulation. Physical studies on the critical condition at either side of impurity accumulation window provide two different physical pictures based on neoclassical impurity transport in the core plasma and on classical theory in the SOL region [12]. Impurity behavior is generally dominated by the radial electric field (Er), which increases or decreases monotonically with the minor radius in LHD standard discharges. Impurity accumulation is always observed in the ion root with a large negative Er (closed blue points). The dashed line is expressed by the constant ion collisionality with the same Er value. Below the solid line, intrinsic impurities are shielded by friction force in the ergodic layer. The open red points indicate recent high power NBI discharges and impurity accumulation does not appear even in the region between two boundaries where impurity accumulation was expected. This suggests that there exists no impurity accumulation in high performance plasmas with high power heating (Pnbi > 10 MW) and it is excellent for realizing fusion plasmas.

2.3. Transition to stationary state without impurity accumulation

The plasmas in the region indicated in yellow (figure 4) have a large negative Er as well as that in low power discharges. A new contribution to impurity transport is required to explain the strong suppression of impurity accumulation. In order to keep the Er contribution (neoclassical one) constant, the specific discharges with constant ion collisionality are selected from those with various heating powers, because the ion collisionality is a good predictor of Er. Figure 5 shows the dependences of carbon density increasing rate (dnC/dt) on normalized ion temperature gradient (R/LT) and carbon Mach number (Mach C) under the constant ion collisionality condition. The impurity pinch is estimated by the increasing rate of carbon density (dnC/dt) at ρ = 0.5. In these discharges, the Er at ρ = 0.9 is negative and around −5 kV/m. The plasmas with high power heating (Pnbi > 10 MW) and it is excellent for realizing fusion plasmas.
of minor radius ($\rho = 0.5$). When the temperature gradient is increased with the heating power, the increasing rate of carbon density (impurity pinch) decreases up to zero and then remains at nearly zero level, that is, stationary state without impurity accumulation (figure 5(a)). A similar correlation is also observed between impurity pinch and carbon Mach number (figure 5(b)). These relationships cannot be explained only by neoclassical impurity transport, which is dominated by the $E_r$ contribution.

2.4. Parameter dependence of carbon density profile

In order to elucidate the new contribution to impurity transport, a database of carbon density profile from steady-state discharges with high power NBI heating has been constructed. All shots have a continuous 13 MW NBI heating power, which consists of tangential beams (co-injection: 6.3 MW, counter-injection: 3 MW) and perpendicular beams (3.7 MW). These discharges are produced with the magnetic axis $R = 3.6$ m and with the toroidal field $B_t = -2.75$ T. The database covers a range of plasmas with averaged electron densities between $1.5 \times 10^{19}$ m$^{-3}$. A number of strong correlations are visible in the database (figure 6). The most striking one is between the Mach number $u_C = \nabla v_{tor}/\nabla v_{th}$ and the carbon density gradient $\rho L_{nC}$ (figure 6(b)). The carbon density profile becomes hollower as the Mach number is increased. A similar strong correlation can also be seen between $\rho L_{nC}$ and the rotation gradient $\nabla u_C = -(\nabla v_{tor})/\nabla v_{th}$ (figure 6(c)). The similarity between figures 6(b) and (c) is due to a high correlation between $u_C$ and $\nabla u_C$, which is a consequence of peaked toroidal rotation profiles that result from central NBI heating. Since temperature gradients are the primary quantity in determining the characteristics of turbulent modes, the correlations between $\rho L_{T}$ and $\rho L_{nC}$ provide a strong signature that turbulence is important in the impurity transport.

3. Impact of NBI torque input on impurity transport

Steady-state discharges have so far been conducted with almost constant NBI heating power, i.e. constant NBI torque input. The toroidal velocity depends on the plasma density and increases when the density decreases [20]. Here, the effect of external torque on impurity transport is investigated by changing the NBI torque input in low collisionality region. Figure 7 shows the change of impurity transport by switching the NBI torque input from co-injection to counter-injection at $t = 4.8$ s. Time evolutions of (a) tangential and perpendicular NBI power, (b) central electron temperature $T_{e0}$ and normalized radial gradient $\rho L_{Te}$ ($\rho = 0.5$), (c) central ion temperature $T_{i0}$ and normalized radial gradient $\rho L_{Tn}$ ($\rho = 0.5$), (d) central carbon density $n_C$ and normalized radial gradient $\rho L_{nC}$ ($\rho = 0.5$), (e) central toroidal rotation velocity $V_t$ ($\rho \sim 0$) and its radial gradient $\nabla V_t$ ($\rho = 0.5$) are indicated. This hydrogen discharge is produced with the magnetic axis $R = 3.6$ m and with the toroidal field $B_t = -2.75$ T.
the co-NBI is injected from 3.3 s to 4.8 s. Then the counter-NBI is injected from 4.8 s to 6.3 s. The perpendicular-NBI is added in order to allow the CXS measurements. The central temperatures \(T_{e0}\) and temperature gradients \(R/L_{e0}\) and \(R/L_{Te}\) at \(\rho = 0.5\) do not change significantly when the beams are switched on at \(t = 4.8\) s. In contrast, a remarkable change of core carbon density \(n_{C}\) and carbon density gradient \(R/L_{nC}\) \((\rho = 0.5)\) are observed when changing the toroidal velocity \(V_t\) and rotation gradient \(u_{tC}\) \((\rho = 0.5)\). The carbon density profile becomes hollow in the last stage of co-injection and a strong peaking of carbon density is observed in the counter injection phase, as shown in figure 8(a). The toroidal boron velocity in the core region increases with time in the phase of co-injection and abruptly changes to inverse velocity (figure 8(b)) after the counter-injection. The rotation gradient indicates the same behavior as the toroidal velocity. This drastic response of carbon density profile to NBI torque input suggests that an external torque input has a large impact on impurity transport.

Studies on parameter dependence of carbon density profile show a deep understanding of external torque input effect. Figure 9 shows the dependence of carbon density gradient on NBI torque input, which is normalized by the average electron density. All data points are estimated at around 1 s after the injection of directed NBI. The NBI beams consist of two co-current beams, one counter beam and two perpendicular beams. The directed NBI power \(P_{d}\) is calculated by subtracting counter-injection NBI power \(P_{co}\) from co-injection one \(P_{co}\). The single NBI denotes each directed tangential beam alone and the mixed NBI the combined beams. Consequently, the total power with mixed NBI is larger than that with the single NBI. In the discharges with counter-NBI injection, the carbon profile becomes peaked and the density gradient at \(\rho = 0.5\) has a positive value. The carbon density gradient decreases with increasing the NBI torque input and an extremely hollow profile of carbon density \(R/L_{nC} \sim -25\) is observed in the combined co-NBI injection with a large torque input. Such a strong hollow profile is comparable to that of ‘impurity hole’, which is found in high ion temperature modes \([17–19]\). It is worth noting that the impurity hole can be produced even in standard confinement regime.

In this experimental series where the NBI torque input is mainly changed, a database of carbon density profiles has also been set up. Figure 10 shows the correlations between the carbon density gradient and various plasma parameters (ion temperature gradient, carbon Mach number and toroidal velocity gradient). One can see several strong correlations in this database. The well-regulated correlation is observed between the Mach number and the carbon density gradient (figure 10(b)) and the hollowness of the carbon density increases with the Mach number. The carbon Mach number extends up to 0.2, which is around five times in comparison with that in the steady state discharges (figure 6(b)). A similar correlation is also observed between \(R/L_{nC}\) and the toroidal velocity gradient (figure 10(c)), but contains two branches due to different total NBI heating powers. The carbon density profiles in higher power discharges with mixed NBI become deeply hollow in comparison with those in lower power discharges with single NBI. The carbon density gradient has a significant decreasing trend with increasing ion temperature gradient. However, there exist some outliers deviating from the main trend and they correspond to a minimum value of the temperature ratio \((T_j/T_e \sim 1.0)\), which leads to the reduction of the turbulence growth rate. Clearly, the toroidal velocity (Mach number) has correlation with the NBI torque input and the independent variables plotted on the x-axes also have
correlations between them (e.g. NBI torque inputs, temperature gradients and rotation): a strong correlation between rotation and ion temperature gradient (not shown) is present. The primary correlation, between rotation (rotation gradient) and impurity peaking is not caused by a single mechanism, but is a non-trivial combination of the correlations between NBI torque inputs, temperature gradients, and rotation. These quantities together determine the impurity transport characteristics in such a way that the overall result produces the strong correlation shown here.

4. Effect of ion temperature gradient on impurity transport in net zero torque discharge

In order to distinguish the effect of ion temperature gradient on impurity transport, the discharges with net zero torque input (balanced NBI injection) have been selected and the parameter dependences of carbon density profile are investigated. The balanced NBI injections with co-injection and counter-injection beams have only a very small torque input ($-0.3 < P_d/n_{e_bar} < 0.3$), which has no influence on impurity transport. The perpendicular NBI beam with the energy of 44keV is added to increase the ion temperature. The carbon Mach number ranges from $-0.015$ to $0.01$ and the rotation gradient from $-0.6$ to $0.1$. There is no significant correlation between $R/L_{nc}$ and these parameters. However, a distinct correlation is found between $R/L_{nc}$ and ion temperature gradient as shown in figure 11, where all data points are estimated at around 1 s after the balanced NBI injection. The carbon density profile becomes hollow with increasing the ion temperature gradient. This suggests that the ion temperature gradient contributes to the strong outward convection in impurity transport and turbulence is important in the impurity transport.

5. Discussions

As indicated in $n$-$T$ diagram for impurity behavior (figure 4), impurity accumulation behavior is basically dominated by neoclassical impurity transport, which strongly depends on the radial electric field ($E_r$), in the plasmas with relatively low power heating. The $E_r$ at the plasma edge is always negative in the impurity accumulation window and the negative $E_r$ values remain even in high power discharges. Here, in order to investigate the neoclassical contribution to impurity transport, the neoclassical impurity flux in high power discharges is calculated by DKES/PENTA code [21]. This allowed the earlier transport coefficients based on the DKES model to be used and momentum conservation to be achieved at least at a fluid moment level. These approaches were extended to include impurities and incorporated into computational models. Figure 12 shows a simulation result for stationary plasmas in high power discharges without impurity accumulation. In this case, there is still no external torque input in the momentum transport equation. The temperatures and densities of multi-species (electron, ion, helium and carbon) are given by fitting the profiles measured in the discharge (121260). The simulation results show that the $E_r$ is negative and the carbon impurity flux is inward in a whole region of plasma ($C ~ -0.5 \times 10^{17} \text{m}^{-2} \text{s}^{-1}$), which results in strong carbon impurity accumulation. The normalized total carbon flux $\Gamma_C/n_{C,D_{11}}$ is still dominated by the flux component due to the $ZeE_r/T_i$ as shown in figure 13, where the neoclassical impurity flux density is decomposed into density gradient $-n_{C,L_{nc}}$, radial electric field $ZeE_r/T_i$ and temperature

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Figure 10. Correlations in NBI torque input discharge database of carbon density measurements at $\rho = 0.5$. The normalized carbon density gradients are plotted as a function of (a) normalized ion temperature, (b) carbon Mach number and (c) normalized toroidal velocity gradient.

Figure 11. Dependence of carbon density gradient on ion temperature gradient at $\rho = 0.5$ in the discharge with net zero torque input. In these discharges, the toroidal rotation velocity is very small.
gradient $-(D_{12}/D_{11} - 3/2)T_C/T_C$ components. The same simulation results are obtained for all discharges with high power heating. Here, it is worth noting that the neoclassical pinch term $Z_e E_r/T_i$ decreases with increasing the ion temperature. If the plasma collisionality is kept constant (the $E_r$ is almost the same), the neoclassical contribution to impurity transport is remarkably reduced in higher ion temperature plasmas [22], which are produced with high power heating. However, in our simulations, the inward neoclassical pinch is still dominant and it is in contradiction with the experimental results in high power discharges. The strong suppression of impurity accumulation cannot be explained by standard neoclassical theory without an external torque input.

In steady state discharges with relatively low power heating, the NBI torque input is not so large and the rotation velocity is so small even at the middle of minor radius because the rotation velocity strongly decreases with increasing the plasma density in the outer region ($\rho > 0.5$) due to parallel viscosity [20]. When the heating power increases largely, significant rotation velocity appears even at $\rho = 0.5$ (figures 5(b) and 6(b)) and the impact of external torque input on impurity transport can be seen clearly in the plasmas with relatively low collisionality as described in section 3. One of possible candidates for the suppression of impurity accumulation is the modification of neoclassical impurity transport due to external torque input. The influence of external momentum sources on plasma flow has been studied in a variety of stellarators [23]. The introduction of sources into momentum balance equation couples directly into ambipolar electric field determination and the $E_r$ in core region is remarkably modified by strong parallel momentum source (toroidal force $\sim 1 \text{ N m}^{-3}$) such as neutral beams. In our experimental condition, the toroidal force due to tangential NBI is less than $0.1 \text{ N m}^{-3}$ and a drastic change of $E_r$ from negative to positive value cannot be expected. It is under investigation to confirm the modification of neoclassical impurity transport by using DKES/PENTA code with an external momentum source, including the change of $E_r$ in high power discharges. On the other hand, for tokamak plasmas, the effect of NBI momentum input on neoclassical transport has been reported in several papers [24–26]. Radial impurity transport fluxes are produced by the direct momentum exchange between injected beam particles and impurities or the radial electric field obtained from momentum balance. These impurity fluxes depend on the directions of beam, toroidal field and plasma current and tend to cancel each other out. Moreover, an inertial effect produced by the beam-induced plasma rotation produces a radial impurity transport flux. The drastic (nonlinear) modification of the neoclassical fluxes would be expected if Mach-one conditions were approached or exceeded. Since the carbon Mach number is less than 0.2 in our experiments, it seems to be difficult to explain a strong hollow profile (outward convection) observed in the carbon density profile. Recently, the effect of poloidal asymmetries in the impurity distribution on impurity transport is discussed [27–29]. The poloidal asymmetries are produced by the centrifugal force and the impact of poloidal

**Figure 12.** Neoclassical simulation with the DKES/PENTA code for stationary plasma in high power discharges. Radial profiles of (a) plasma temperatures ($T_e, T_i = T_C$), (b) particle densities ($n_e, n_{He}, n_C$), (c) radial electric field and (d) particle fluxes ($\Gamma_e, \Gamma_{He}, \Gamma_{He}, \Gamma_C$) are indicated.

**Figure 13.** Decomposition of neoclassical carbon flux density calculated with DKES/PENTA code. The carbon flux is normalized by $n_C D_{11}$ and decomposed into each component (density gradient, $E_r$ and temperature gradient).
asymmetries on neoclassical convection depends on collisionality and plasma gradients. This topic is beyond the scope of the present experimental work and it is one of our future issues.

Another probable candidate for suppressing impurity accumulation is turbulent impurity transport including toroidal rotation effect. Since the strong connections between particle and toroidal momentum transport are presented, the turbulent impurity transport is also affected by toroidal rotation through momentum transport. The impact of the toroidal rotation and its radial gradient can become important for impurities due to heavier mass and lower thermal velocity (larger Mach number) [30–32]. The turbulent impurity flux is expressed by

\[
\Gamma_\text{\textcircled{i}} = n_D (R/Ln_{\text{ZC}} + C_{\text{\textcircled{T}}} R/LT + C_{\text{\textcircled{\mu}}} \mu_i + C_p),
\]

where in addition to diagonal diffusion \(R/Ln_{\text{ZC}}\), thermodiffusion \(C_{\text{\textcircled{T}}} R/LT\), and pure convection \(C_p\), an additional off-diagonal contribution \(C_{\text{\textcircled{\mu}}} \mu_i\) is presented, proportional to the gradient of the toroidal velocity. The experimental impurity behaviors in the ASDEX upgraded tokamak have been well reproduced by the theoretical modeling, which is due to a combination of the turbulent regime and an impurity flux by rotation gradient [31, 32]. In the cases with dominant ITG modes, both thermodiffusion and rotation terms due to toroidal rotation are directed outward. The peaking of boron profile is reduced with increasing rotation velocity (the boron Mach number) and its radial gradient. In our experimental conditions, ITG modes can be driven in high temperature plasmas with \(R/LT < 5\) [33] and the increase in carbon hollowing with increasing the carbon Mach number is qualitatively consistent with the theoretical prediction. Recently, non-linear gyrokinetic simulations have shown that turbulent impurity transport (diffusion) is maximized when the electron and ion heat fluxes are comparable [34]. The effect of heat fluxes ratio on impurity transport will be investigated with ECH and ICH heating systems in near future.

In LHD, a strong hollow profile of impurities, the so-called ‘impurity hole’, has been observed in high ion temperature modes [17–19]. In these discharges, a large toroidal rotation is always accompanied with the high ion temperature gradient in the core plasma [20]. Certainly, the ion temperature gradient has an effect on impurity transport and the carbon profile becomes hollow with increasing the temperature gradient as observed in the discharges with net zero torque input (figure 11). However, the strong correlation between \(R/Ln_{\text{ZC}}\) and the Mach number in our results indicates that the toroidal rotation also plays an important role in the impurity transport.

In impurity transport, it is very important to investigate the behavior of the main plasma density gradient, which also plays an important role in the determination of the neoclassical and turbulent transport parameters. Generally speaking, the electron density profile changes in the same manner as the carbon density profile when the plasma parameters (density, heating power and rotation etc) are scanned. However, the changes in the electron density and its gradient are not so large in comparison with those in the carbon density profile. The behavior of the main density profile will be investigated to elucidate the physical reason for the peaking (hollowing) of impurity density profile as one of future tasks.

Finally, in fusion devices, it is difficult to keep a large external torque input and stationary operation at low or zero injected torque is essential. As for the problems to be solved, it can be pointed out that spontaneous rotation observed in LHD [35] is a key issue and the effect of intrinsic toroidal rotation on impurity transport should be investigated in future.

### 6. Summary

Steady state discharges in LHD have been conducted with higher NBI heating power (\(P_{\text{nbi}} > 10\) MW) and the operational regime was extended to high temperature and high density region. Impurity behavior has been investigated to explore favorable scenarios without impurity accumulation. A dramatic change of impurity behavior is found in the high power discharges. In the discharges with lower NBI heating power, impurity accumulation has been always observed in a specific density (plasma collisionality) range. However, the high power discharges reveal strong suppression of impurity accumulation over the entire density range and a new operational regime without impurity accumulation is found in steady state discharges. Such a drastic change of impurity behavior is caused by the increase in ion temperature gradient and Mach number due to higher NBI heating power. The carbon density profile structure has been analyzed by CXS measurements and several strong correlations are seen between \(R/Ln_{\text{ZC}}\) and various plasma parameters. The carbon density profile becomes hollow with increasing the carbon Mach number and toroidal rotation gradient. The carbon peaking also decreases with increasing the ion temperature gradient, which is closely connected with turbulence.

Momentum transport experiments with changing the NBI torque input provide a more convincing result in the impurity transport. A remarkable change of carbon density in the core plasma is observed by switching the direction of NBI torque input with almost the same NBI heating power. The co-injection beam leads to a hollow profile of carbon density and the counter-injection beam a peaked carbon density profile. In this discharge, there is a big change in the toroidal rotation velocity in the core plasma though the plasma temperatures remain almost unchanged. The carbon density gradient strongly depends on the NBI torque input and the strong co-injection results in an extremely hollow profile of carbon density, which is equivalent to that of ‘impurity hole’ in high ion temperature modes. In this experimental database, strong correlations between the \(R/Ln_{\text{ZC}}\) and rotation plasma parameters (carbon Mach number and its radial gradient) are observed in a wide range of each parameter. It can be said that the toroidal rotation plays an important role in the impurity transport.

The high power discharges with net zero torque input (balanced NBI injection) are very useful for investigating the effect of ion temperature gradient on impurity transport,
since the toroidal rotation is so small and there is no significant correlation between $R/L_{nc}$ and the rotation parameters. A distinct correlation is observed between $R/L_{nc}$ and the ion temperature gradient and the carbon density profile becomes hollow with increasing the ion temperature gradient. It can be concluded that the ion temperature gradient also contributes to the strong outward convection in the suppression of impurity accumulation.

The strong suppression of impurity accumulation cannot be explained only by neoclassical theory, which predicts a negative radial electric field and inward impurity flux for high Z impurities. In fact, the simulation code DKES/PENTA, which has been recently extended in order to include momentum conservation between multi-species particles, indicates that the radial electric field is negative and the impurity flux is inward. One of the most probable candidates for the suppression of impurity accumulation is turbulent impurity transport including toroidal rotation effect, which has been investigated in tokamak plasmas. The strong correlations between $R/L_{nc}$ and plasma parameters such as toroidal rotation (its radial gradient) and ion temperature gradient are qualitatively consistent with the theoretical predictions for tokamak plasmas. However, the impurity transport simulation for helical plasmas with an external torque input would be required in future, including both neoclassical and turbulent transport.

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