Impurity Behavior in LHD Long Pulse Discharges

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Introduction

Impurity control is one of the important issues for realizing a fusion reactor. While many experiments on impurity transport have been performed in tokamaks and stellarators with short pulse discharges, few experiments have been done with long pulse discharges, in particular, on stellarators. Therefore, impurity behavior was investigated in long pulse discharges on LHD, which is a superconducting large helical device. In a variety of long pulse discharges [1-4], we found that metal impurity accumulation was observed in only hydrogen discharges in a narrow density window of around 2 x 10^{19} m^{-3}. Spectroscopic and soft x-ray measurements show an increase of radiation from metal impurities (mainly iron). A significant increase of core radiation was observed in radiation profiles from bolometry measurements. In this paper, the impurity behavior in NBI heated long pulse discharges will be reported and the density dependence will be discussed with neoclassical impurity transport in the core plasma.

Impurity behavior in long pulse discharges

Figure 1 shows a typical long pulse discharge with impurity accumulation and pump-out. A remarkable increase of central radiation (r = 0) is observed despite of almost constant radiation level at the peripheral region (r = 0.945) in the first half period of the discharge. Then the central radiation decreases gradually with time during the constant gas puffing. Clear evidence of impurity accumulation was observed in a peaked profile of radiated power density. Spectroscopic and soft x-ray measurements indicate that the main metallic impurity is iron, which is an element of the plasma wall material. In the high-density region ($\bar{n}_e > 3\times10^{19} m^{-3}$), the central radiation decreases despite of the density increase and the radiation profile tends to return to a hollow one. This implies that the metallic impurities accumulated in the core region are pumped out in the high-density region.

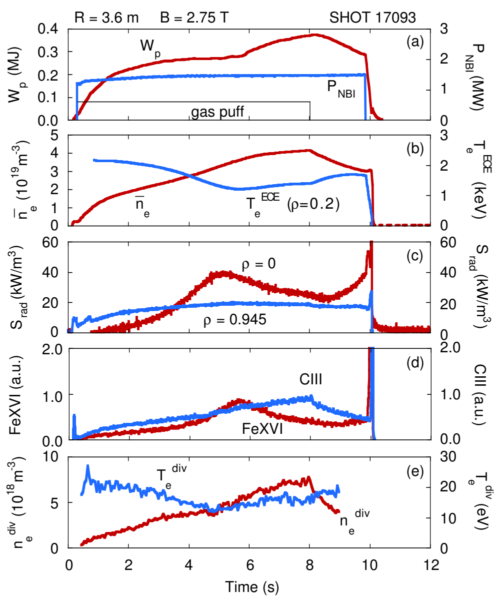

Fig. 1 A typical long pulse discharge with impurity accumulation and pump-out.

The accumulation behavior was also observed in long pulse discharges keeping the plasma density constant. Figure 2 shows the time evolutions of central radiated power density and the most prominent metallic emission (FeXXIII), which originates from the central region of the plasma, for the discharges with different plasma densities. Remarkable temporal increases of the central radiation and the iron line emission were found for only the discharge with $\bar{n}_e = 2.7\times10^{19} m^{-3}$. Strong core radiation was also observed.

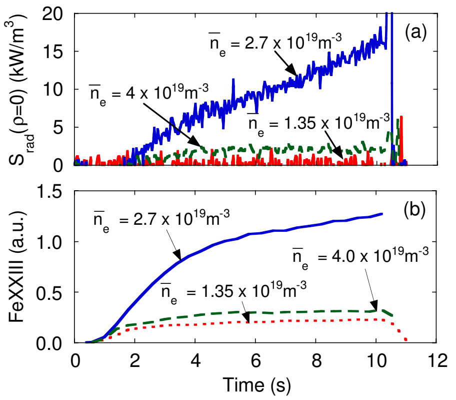

Fig. 2 Time evolutions of (a) central radiation and (b) FeXXIII emission for the discharges with constant densities.

Assuming that the corona equilibrium can be used for high-Z ions (Fe) in the plasma core, the total impurity density was estimated from the radiation emissivity $Q_{rad} = n_e n_I L_I(T_e)$, where n_I is the total density of impurities and $L_I(T_e)$ is the so-called cooling rate. Figure 3 shows the time evolution of central iron density obtained from the radiation emissivity (r = 0), together with a metallic impurity line emission (FeXVI) viewed along the central chord of the plasma. To estimate the radial profile of iron density, we investigated the intensity of the FeXVI emission using the profiles of electron temperature and density, coupled with the impurity transport code (MIST). The central concentration of iron is given by the iron density in Fig. 3(b). The radial profile of total impurity density and the charge state distribution can be calculated by giving the diffusivity and the convection velocity of impurities in the MIST code. In the initial stage of the discharge, the profile of iron density is supposed to be approximately flat. Therefore, we fixed a flat profile of iron density at t = 1.5 s and determined the density profiles at t = 5 and 7.3 s so that the FeXVI emission satisfied the ratio of the intensity measured at each time. Figure 4 shows the radial profiles of iron density at different times of the discharge. A remarkable peaked profile of iron density is observed at t = 5 s and the profile returns to a flat one at t = 7.3 s. This implies that the metallic impurities are accumulated in the density range of $\bar{n}_e = 1 \sim 2.5\times10^{19} m^{-3}$ and pumped out in the higher density region.

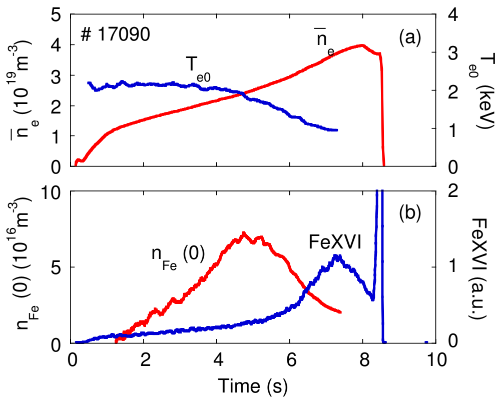

Fig. 3 Time evolutions of central iron density and the Fe XVI emission originating from the peripheral plasma.

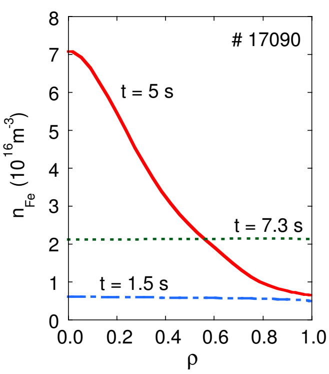

Fig. 4 Radial profiles of iron density at different times for the shot 17090.

Neoclassical analysis of impurity transport

The radial impurity flux was investigated for various collisionality regimes. For the case of low collisionality (low density and high temperature), the impurity flux is given by [5]

$$\Gamma_I = -D_S n_I (n_I'/n_I - Z_I E_r/T_I + \alpha T_I'/T_I) \qquad (1)$$

where D_S and E_r is the diffusivity and the radial electric field, respectively, and α is a collisionality dependent factor. If the impurities are in a regime of 1/ν or collisionless detrapping, the flux is dominated by the term due to the electric field, in particular, for high-Z impurities. The formation of E_r is determined from an ambipolarity condition for the radial fluxes of electrons, ions and impurities. If the electron flux is the dominant flux in a very low collisionality regime, the ambipolar electric field becomes positive (electron root). In this case, the impurity flux tends to go outward. When the collisionality increases, the ion flux becomes dominant and the electric field turns to be negative (ion root). Then the impurity flux tends to go inward. For the case where the impurities are in the plateau regime and the ions in the banana regime, the impurity flux is given by

$$\Gamma_I = -D_{BP} n_I (n_I'/n_I + 3T_I'/2T_I - Z_I n_i'/n_i - 3Z_I T_i'/2T_i) \qquad (2)$$

based on neoclassical transport for axisymmetric devices [6]. For high-Z impurities, the flux is dominated by the last two terms, which drive the impurities inward because n_i' and T_i' are generally negative. When the plasma density increases, the impurities enter in the Pfirsch-schlüter regime with high collisionality. If only the interaction of heavy impurities with the background ions is important, the impurity flux is written as

$$\Gamma_I = -D_{PS} n_I (n_I'/n_I - T_I'/2T_I - Z_I n_i'/n_i + Z_I T_i'/2T_i) \qquad (3)$$

In this regime, the last two terms also dominate the impurity behavior. The density term is directed towards the plasma axis and is responsible for peaking of the impurity density. The temperature term is of the opposite sign and prevents such a peaking, i.e. is responsible for the so-called 'temperature screening'. In LHD, since the density profile is flat or hollow in the discharges with gas puffing and the temperature profile is nearly parabolic, the impurity flux tends to go outward in the plasma core and it leads to a flat profile of the impurity density.

By taking into account the various impurity transport regimes described above, one can see the impurity behavior in a n-T diagram as shown in Fig. 5, where the plasmas with impurity accumulation (closed circles) are distinguished from those without accumulation and with pump-out (squares). The solid line represents the transition between the plateau regime and the Pfirsch-schlüter regime for iron impurity. This boundary is calculated in consideration of the collision with light impurities (C, O), whose concentrations are determined so that Z_{eff} has the value of about 2.5 obtained in the experiments on LHD. The broken line represents the transition between the electron root and the ion root for background plasma. This indicates a critical point of the specific space where the plasma has multiple solutions for the ambipolar electric field. The point was calculated by an analytical model [7] with the typical profiles of temperature and density measured in long pulse discharges at ρ = 0.2. On the whole, the impurity behavior obtained in long pulse discharges is qualitatively in agreement with the neoclassical impurity transport. In the low density and high temperature region, the high-Z impurities may be expelled by the positive electric field or diffused out because of nearly zero electric field. As indicated in Fig. 5, it is not so easy to obtain the electron root in the plasma core, but it is possible to obtain in the peripheral region [8]. Furthermore, small positive electric fields were observed even in the density range of ion root near the transition to electron root [8]. The boundary of impurity accumulation in the low collisionality regime may be shifted to higher collisionality regime. In the intermediate regime with negative electric field (ion root), the high-Z impurities are accumulated in the central plasma due to the electric field in the 1/ν regime or the temperature gradient in the plateau regime. When the impurities enter in the PS regime, the accumulated impurities are pumped out by the dominant contribution of the temperature gradient term on account of the flat density profile and the parabolic temperature profile. If the plasma density is raised up quickly, impurity accumulation does not occur because of the temperature screening effect in the PS regime.

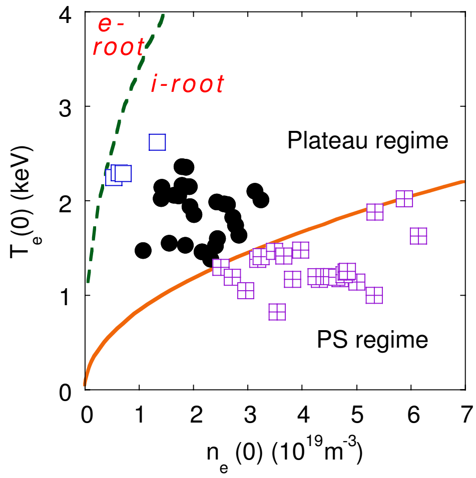

Fig. 5 A n-T diagram for impurity behavior in long pulse discharges. The closed circles indicate the plasmas with impurity accumulation and the open squares indicate the plasmas without accumulation. The squares with a cross indicate the plasmas with pump-out or without accumulation.

Conclusions

Accumulation behavior of high-Z impurities has been observed in NBI heated long pulse discharges with constant density on LHD. The intrinsic metallic impurities (mainly iron) were accumulated in a specific range of the operational plasma density. For density ramp-up discharges, impurity accumulation and pump-out were observed during the discharge and a clear density window for accumulation was found. Neoclassical analysis shows that the radial impurity flux is dominated by the convection component, which changes the sign (inward or outward) for different transport regimes. The observed impurity behavior is in qualitative agreement with the neoclassical impurity transport.

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