1. Introduction

Many trials on ion heating have been done hitherto in the LHD mainly using NBI and ICRF. Successful ion heating was found in ICRF minority heating (H-minority, He-majority). The ion heating, however, has been still insufficient in H$_2$ and He NBI discharges [1] because of the high beam energy ($E_{NBI}=150-180$keV). The NBI absorption power, $P_{abs}$, is mostly deposited in bulk electrons ($P_e/P_{abs}$~80%) due to a higher value of $E_{NBI}/T_e$ ratio (~50). Then, the $T_i$(0) saturates at less than 2.5keV [1].

Recently, neon gas was seeded in order to increase the $P_{abs}$ and to reduce the bulk ion density, $n_i$, in low-density discharges. As a result, the ratio of $P_i/n_i$ ($P_i$: direct deposition power from fast ions to bulk ions) could be increased roughly by 5 times in these neon discharges. A $T_i$(0) of up to 5keV was successfully obtained under a neutral beam injection power, $P_{NBI}$, of 8 MW and a linear relation was also found between the $T_i$(0) and $P_i/n_i$ [2,3], although the hydrogen amount could not be sufficiently reduced.

On the other hand, an H$_2$ ice pellet has been injected to achieve a peaked profile followed by the confinement improvement. However, an apparent temperature increase was not observed, although the operational density range was successfully extended [4]. Thus, a carbon pellet having a much higher melting point was injected as an alternative way to modify the density profile and to increase the $P_{abs}$ at the plasma center using a newly installed impurity pellet injector [5]. In this paper, results on the impurity pellet injection are briefly reported in terms of the ion heating [6].

In the LHD the central ion temperature, $T_i$(0), has been routinely measured by a crystal spectrometer with a CCD detector observing the Doppler broadening of x-ray lines of He-like TiXXI and ArXVII [7]. No other methods to measure the $T_i$(0) exist in the present LHD.
2. Plasma Response to impurity pellet injection

Spherical and cylindrical impurity pellets (size: 0.5-1.0mm) of C(Z=6), Al(13), Ti(22) and Mo(42) have been injected into NBI discharges ($R_{ab}$=3.60m). Typical results are shown in Fig.1. Injected pellet sizes were 1.0mm$^\phi$x1.2mm$^L$, 0.8mm$^\phi$x0.5mm$^L$, 0.6mm$^\phi$x0.5mm$^L$ and 0.4mm$^\phi$x0.4mm$^L$ for C, Al Ti and Mo, respectively. When $n_e(r)=$const. and $T_e(0)=2keV$ are assumed, a density rise ($\Delta n_e$) of 2.1, 0.65, 0.54 and 0.42x10$^{13}$cm$^{-3}$ is expected. The results roughly satisfy with the expectation and it means that the injected pellets are fully ablated and confined in the plasma.

The plasma response is clearly different among the 4 elements. In case of the carbon pellet the density quickly goes up and the plasma can be heated up as appeared in the plasma stored energy and central ion temperature behaviors. In case of heavier elements, however, the plasma is immediately cooled down. The Mo pellet injection is the severest case showing the plasma collapse. The $T_e(0)$ drops from 2.7keV to 0.7keV within 100ms after injection. During the temperature decay phase a strong MHD activity, which can induce the plasma collapse, is not observed at present. Then, the temperature drop is mainly triggered by the ionization and radiation losses. The two losses ($P_{\text{ionize}}$, $P_{\text{rad}}$) and maximum ionization stages ($q^*$) at plasma center are calculated (see Fig.2). In the calculation $T_e(0)=2keV$ and $n_e=2x10^{13}$cm$^{-3}$ is assumed and the size of pellets is fixed in sphere with 0.5mm$^\phi$ diameter. It is clear that the radiation loss is comparable to the NBI absorption power. When the $T_e$ drops, of course, the $P_{\text{rad}}$ becomes larger, and exceeds the $P_{\text{abs}}$. The energy confinement time ($=W_p/P_{\text{abs}}$) of the discharge is $\sim$100ms and the decay time of $W_p$ after Mo pellet injection is $\sim$60ms. These similar values also indicate the thermal collapse mainly due to the radiation loss.

Fig.1 Plasma response to C, Al, Ti and Mo pellets (from left to right). Plasma stored energy ($W_p$), line-averaged density ($n_e$), ion temperature ($T_i(0)$), port-through power ($P_{\text{NBI}}$), ionized power ($P_{\text{abs}}$) and total radiation loss ($P_{\text{rad}}$) (from top to bottom).
3. Increase of ion temperature after C pellet injection

A typical result for the large pellet (1mm$^3$x1mm$^1$) injection is shown in Fig.3 (right). The carbon pellet was injected in Ne-seeded discharges. Waveforms of the Ne-seeded NBI discharge without carbon pellet are also traced in Figure 3 (left) for comparison. Both discharges are carried out for the $R_{ax}$=3.60m configuration. The density of $n_e$=0.4-0.5x10$^{13}$ cm$^{-3}$ is produced mainly by the puffed neon and recycled hydrogen. A $T_i(0)$ of 3keV is sustained during the Ne-seeded discharge (see Fig.3(a) left). When the carbon pellet is injected, the $T_i(0)$

Fig.2 Ionization stage ($q^+$), Ionization loss ($P_{\text{ionize}}$) and radiation loss ($P_{\text{rad}}$) as a function of nuclear charge after impurity pellets are evaporated. The $P_{\text{ionize}}$ and $P_{\text{rad}}$ is calculated for ablation of spherical pellet with a diameter of 0.5mm$^6$.

Fig.3 Ne-seeded NBI discharges without (left) and with (right) carbon pellet injection. (a) central ion temperature, (b) NBI power (solid: port-through power, dashed: absorption power), (c) line-averaged electron density (Ne: neon gas puff), (d) density peaking factor ($n_e(0)$: central electron density, $<n_e>$: line-averaged electron density), (e) electron temperature from ECE, (f) central toroidal rotation speed and (g) radiation power (dashed: CIII intensity in arb.
gradually increases and reaches 5keV. The lack of $T_i$ data after the pellet injection is caused by a decrease in ArXVII emission due to the sudden $T_e$ drop.

In low-density discharges, the beam-ion slowing-down time ($\tau_s$) becomes quite long because of the high beam energy (e.g. $\tau_s>1$s for $n_e<1\times10^{13}$cm$^{-3}$) and the beam-stored energy becomes also very large. Then, the heat flux from the beam ions strongly influences the pellet ablation [8]. The pellet is ablated at outer region of plasmas in low-density range. Therefore, the NBIs #2 and #3 are injected just after the pellet injection in order to avoid ablation at the outer plasma region and to achieve a central particle deposition. This was very effective in increasing the $T_i(0)$. The density profiles are shown in Fig.4. The density peaking factor increases up to $\sim2.5$ after carbon pellet injection, whereas it is around 1 for the Ne-seeded discharge (see Fig.3(e)). The injected carbon ions probably contribute to the formation of the density peaking. From the viewpoint of the experience on this impurity pellet injection, a heavier element is seemed to stay in the plasma core longer time.

Due to the density peaking, the central toroidal rotation speed, $V_t$, is largely increased and reaches 35km/s, which corresponds to 12% of the carbon ion thermal velocity. The $T_i(0)$ continuously increases, whereas the $P_{abs}$ becomes constant after $t=1.5$s. Improvement of the ion transport, at least at the plasma center, is expected. The similar $T_i(0)$ increase is also observed for $R_{ax}=3.75$m configuration having a larger $\varepsilon_{h, eff}$. Ion transport analysis is currently underway, based on the estimation of H, C, and Ne ion densities in both discharges.

References