Ion Heating Experiments Using Perpendicular Neutral Beam Injection in the Large Helical Device

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Perpendicular neutral beam (P-NB) injector was installed in the large helical device (LHD), and utilized for high-power ion heating and measurement of ion temperature profile by charge exchange spectroscopy. The ion heating experiments have a significant progress using P-NB, and the high-ion-temperature of 5.2keV was achieved at plasma center. The peaked profile of ion temperature with steep gradient of ion temperature was observed. The enhancement of toroidal flow was observed with the ion temperature rise in the core region. The transport analysis shows the improvement of anomalous transport in the core region, when the high ion temperature is realized.

Keywords: perpendicular NBI, ion heating, charge exchange spectroscopy, beam fueling, toroidal rotation, ion thermal transport

1. Introduction

Ion temperature is one of the most important parameters to realize burning plasmas in magnetically confined fusion plasmas.

Before 9th experimental campaigns of the large helical device (LHD), ion heating experiments were performed by tangential neutral beam (NB) injection. There are three beam lines of negative-ion-based NB with very high beam energy of 180keV, and total port-through beam power was beyond 13MW. However, such high energy beam over the critical energy (E_c~120keV for plasmas with T_e~4keV) mainly heats electrons, thus ion heating power was relatively low. In order to increase the net ion-heating power, the ion heating experiments were performed in the high-Z discharge, and the high-ion temperature of T_i=13keV was realized [1-2], showing high potential high-temperature plasma confinement in helical devices.

For ion heating experiment in low Z plasmas, low energy and high current NB was required, and perpendicular NB (P-NB) with low beam energy of 40keV and port-through power of 3MW was installed and started the beam injection in 9th experiment campaign of LHD, and the power was upgraded to 6MW at 10th experimental campaign [3]. The NB has a high ion-heating efficiency of 80% for plasmas with T_e=4keV, and the ion heating power was significantly increased in LHD.

The P-NB can be utilized for profile measurements of ion temperature by charge exchange spectroscopy (CXS) [4], thus ion heat transport can be experimentally estimated. Moreover, the P-NB has a high particle fueling rate due to the high beam current of 150A, and is also utilized for particle fueling and control of density profile. In this paper, recent results of high-ion-temperature experiment using P-NB in LHD are presented, and the density profile dependence of ion temperature, ion transport property, toroidal flow associated with high-ion-temperature are discussed.

2. Experimental

The LHD is a world-largest helical device with major radius of 3.9m and averaged minor plasma radius of 0.6m. The toroidal and poloidal periods are n=10 and m=2, respectively. The plasmas are heated by electron cyclotron resonance heating (ECH) of 2MW, ion cyclotron heating (ICH) of 2MW and three tangential negative-ion-based NBIs with total port-through power of 14MW. A perpendicular NBI with low energy of 40keV was installed in 5-O port of LHD in 2005. Four positive ion sources were mounted on the beam line and the total port-through power is 6MW. Two power supply systems (#4A and #4B) can independently control the beam operation such as pulse timing, beam energy, beam duration and so on. The nominal pulse duration is 10 sec, and the beam species is hydrogen. The beam injection with total port-through

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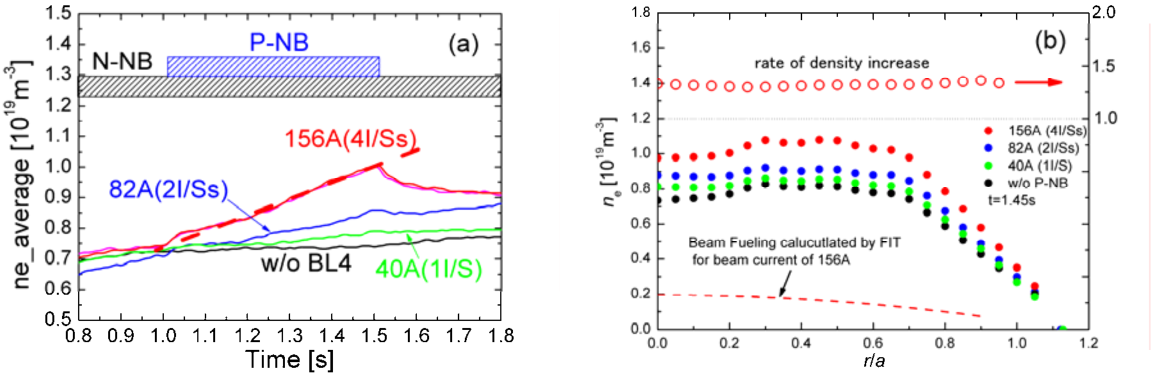

Fig. 1. (a) The response of line averaged electron density with P-NB injections. (b) The density profiles with P-NB injection of 0A, 40A, 82A and 156A. The profile of density increase is shown in upper region. The beam fueling rate calculated by FIT code is also shown in the bottom region, which is consistent with the observed density increase.

power of 7MW was achieved in 10th experimental campaign.

Two systems of active CXS were installed for the P-NB as a probe beam. One is toroidal system having toroidal line of sights and can measure profiles of ion temperature and toroidal rotation of the plasmas. The other is poloidal system having poloidal line of sights and can measure profiles of ion temperature and poloidal rotation of the plasmas. The P-NB is modulated (100msec ON and 100msec OFF) for CXS measurement to acquire the background signal.

3. Results and Discussions

A low beam energy and high current beam has a large particle fueling rate. In order to investigate beam fueling, the beam current of P-NB was performed by changing the number of operating ion source with the same gas condition. The electron density increases with the beam current, which is shown in Fig. 1(a) and the increase rate of $3x10^{16}m^{-3}s^{-1}A^{-1}$ or $2.3x10^{20}s^{-1}MW^{-1}$ was obtained. The change of the density profile and the profile of density increase rate are shown in Fig. 1(b). The density increase rate has a flat profile. The deposition profile is considered to be broad profile because of low density of the target plasma. The beam deposition calculated by FIT code, which is also shown in Fig. 1(b), is consistent with the experimental results.

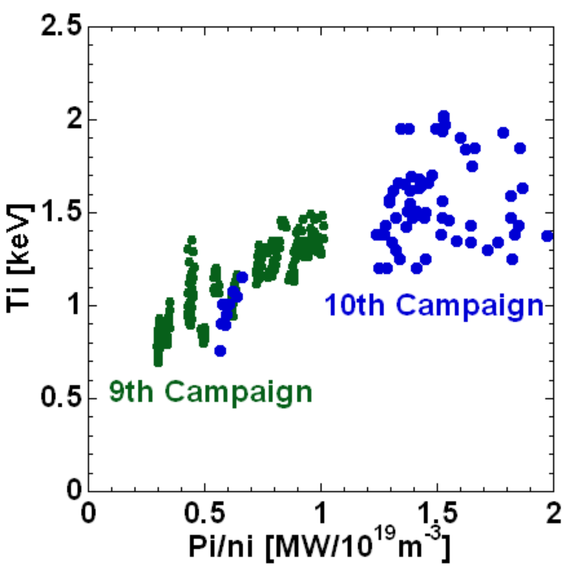

Fig. 2. The ion temperature as a function of ion heating power.

The P-NB power dependence of ion temperature was investigated in the plasmas heated by only P-NB. The maximum ion temperatures of each discharge are plotted in Fig. 2 as a function of ion heating power normalized by the ion density. In this figure, it is clearly seen that the ion temperature increases with ion heating power. It is also experimentally confirmed that the ion temperature increases with P-NB power in the other heating condition such as full power heating with tangential NBs.

The high ion temperature experiments using P-NB were performed and central ion temperature of 5.2keV was realized with the central electron density of $1.2x10^{19}m^{-3}$, which is shown in Fig. 3. The high ion temperature regime was extended toward high density plasmas, and the central ion temperature of 3keV was achieved with the central electron density of $3.2x10^{19}m^{-3}$. The central electron temperature is lower than ion temperature in low density region, indicating the strong ion heating. The electron and ion temperatures are almost same in high density region. This is considered to be attributable to short equi-partition time. These high ion temperature were realized in the

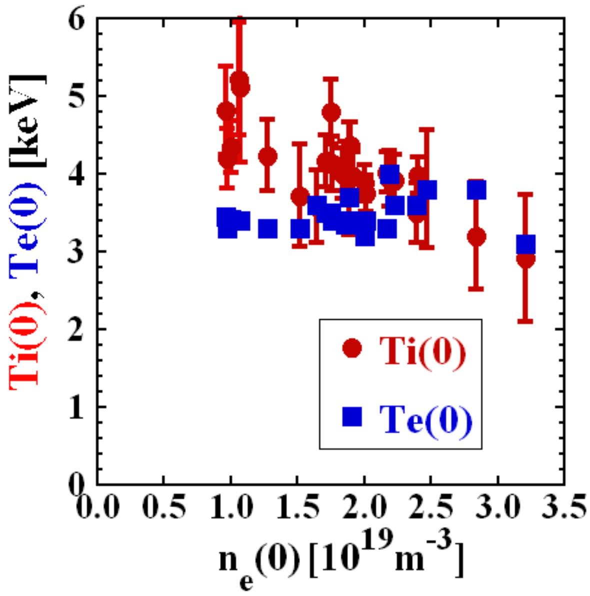

Fig. 3. The central ion temperature as a function of central electron density. The central electron temperature at the time with maximum ion temperature is also shown.

density decay phase after superimpose of tangential NBI on the P-NB heated plasmas. The time trace of ion temperature, line averaged electron density and the central density divided by line averaged density as a density peaking factor are shown in Fig. 4. After superimpose of tangential NBs heating (t=1.1sec), the electron density decreases, and the ion temperature increase and reaches the maximum values at t=1.35sec. Then the ion temperature starts to decrease gradually while the electron density continues to decrease. The peaking factor increases in the P-NB heating phase and decreases after superimpose of tangential NBs. This is a general tendency in LHD plasmas; the density profile becomes peaked one in P-NB heating plasmas and flat or hollow one in tangential NBs. The peaking factor of the electron density keeps still high value when ion temperature reaches the maximum, while the electron density decreases quickly. Therefore, it seems that the peaking factor of electron density is important for ion temperature rise and the peaked density profile is preferable to realization of high ion temperature.

Figure 5(a) shows the profiles of ion temperature at P-NB phase (t=0.95sec), maximum ion temperature phase (t=1.35sec) and after the decrease of ion temperature (t=1.75sec). The ion temperature has a peaked profile and a steep gradient is formed when ion temperature becomes high. The electron temperature is 4keV at the center and is almost same at R>4.2m when t=1.35sec. The large toroidal flow with velocity of 60km/sec was generated in the core region, when the high ion temperature was realized, which is shown in Fig. 5(b). The flow direction is consistent with

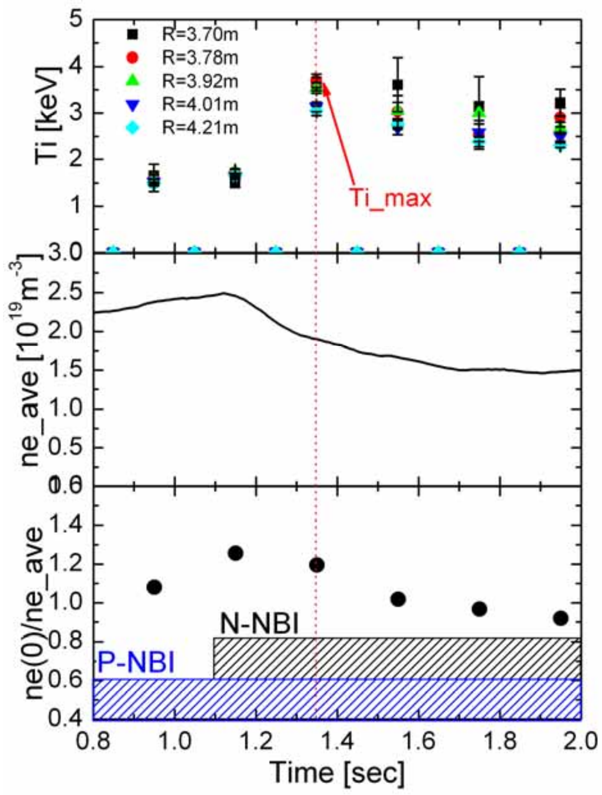

Fig. 4. The ion temperature (upper), line averaged electron density (middle) and a peaking factor (bottom) given by the central density normalized by the line averaged density are shown, respectively.

that of tangential NB injection. These observations indicate strong correlation between ion transport and toroidal rotation. The poloidal rotation in core region can not be observed when ion temperature becomes high, because the carbon impurity has a strong hollow profile associated with ion temperature rise. This "impurity hole" also shows strong correlation with ion temperature rise. The outward flow of carbon impurity against a negative gradient of carbon density was also observed. The large error bars of ion temperature in core region with t=1.35sec in Fig 5(a) are attributable to formation of impurity hole. The neoclassical calculation shows negative radial electric field (ion root), while the impurity pumping-out can be expected by electron root in neoclassical theory. Therefore the understanding of impurity hole formation in the neoclassical ion root is a new subject related to the high-ion temperature experiments.

The neoclassical ion thermal diffusivity does not change significantly in core region [5], which is shown in Fig. 5(c), while ion temperature increases more than twice. In such a low collisional regime, the neoclassical ion flux without electric field strongly depends on ion temperature as $T_i^{7/2}$.

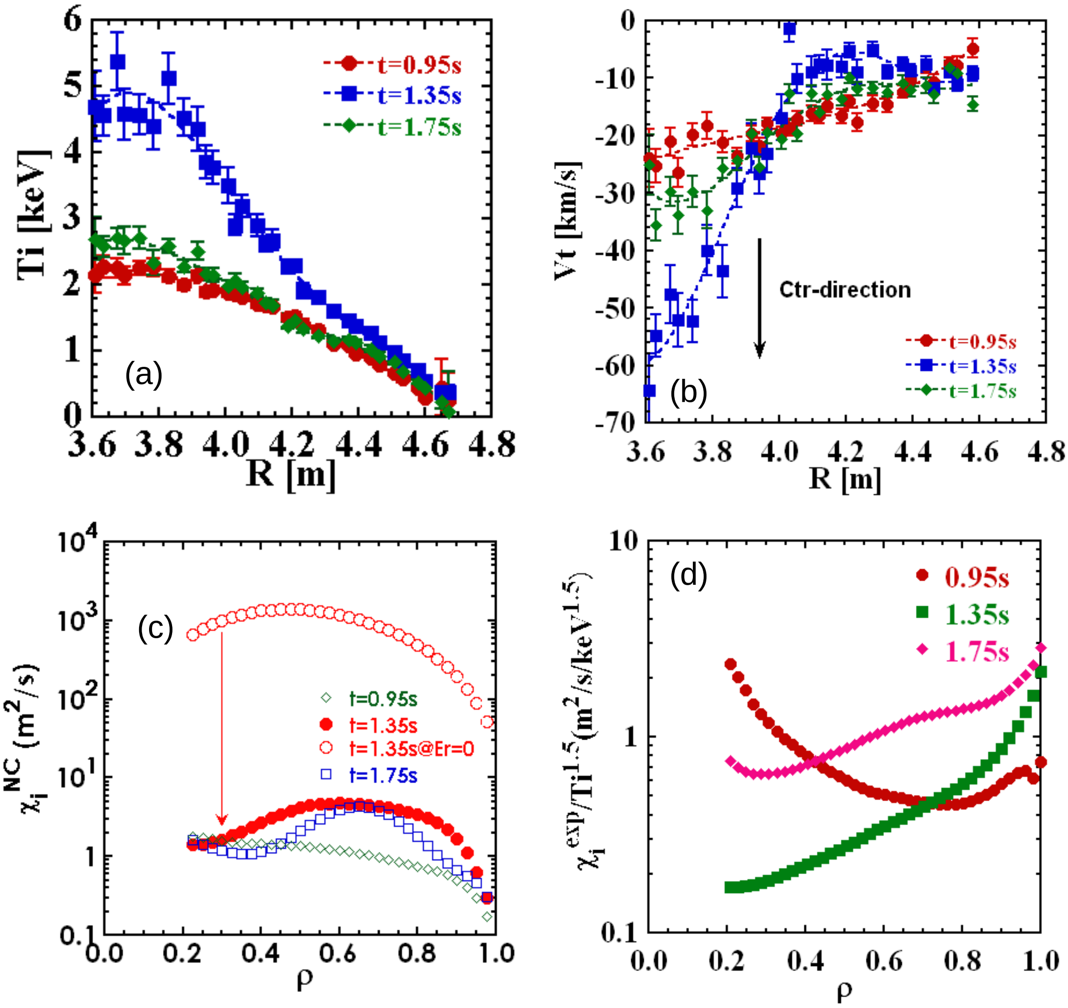

Fig. 5. (a) The profiles of ion temperature of the plasma heated by only P-NB (*t*=0.95sec), just after superimpose of N-NB (*t*=1.35sec) and mainly heated by N-NB (*t*=1.75sec). (b) The toroidal rotation profile at the same time with (a). (c) The neoclassical ion-thermal diffusivity w/ and w/o neoclassical ambipolar radial electric field. (d) The ion thermal diffusivity obtained by power balance analysis.

The degradation of ion transport is considered to be significantly suppressed by negative radial electric field. The neoclassical electron diffusivity also remains unchanged in high ion temperature phase. The ion thermal diffusivity normalized by gyro-Bohm factor, which is estimated by power balance analysis, is shown in Fig 5(d), and the significant reduction of thermal diffusivity was clearly observed in core region, when ion temperature increases. Therefore, it is considered that the reduction of anomalous transport occurs when ion temperature increases.

3. Conclusion

The installation of P-NB injection was significantly progressed high ion temperature experiments on LHD; one is upgrade of ion heating power, and the other is profile measurements of ion temperature, toroidal and poloidal flow, impurity density. The high ion temperature over 5keV was achieved and extended toward high density plasmas. The large toroidal flow and impurity hole were observed in core region associated with ion temperature rise. The negative radial electric field (neoclassical ion root) significantly suppresses the degradation of ion thermal diffusivity, and reduction of anomalous transport was observed in core region. These results are still preliminary and not fully understood yet. The systematic experimental study and neoclassical viscosity analysis are in progress.

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