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

Kenichi NAGAOKA, Masayuki YOKOYAMA, Yasuhiko TAKEIRI, Katsumi IDA, Mikiro YOSHINUMA, Seikichi MATSUOKA[1)], Hisamichi FUNABA, Shigeru MORITA, Takashi MUTOH, Tetsuo SEKI, Katsunori IKEDA, Masaki OSAKABE, Katsuyoshi TSUMORI, Yoshihide OKA, Osamu KANEKO and the LHD Experimental Group

National Institute for Fusion Science, Toki 509-5292, Japan
[1)]*Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan*

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A perpendicular neutral beam (P-NB) injector was installed in the Large Helical Device (LHD) and utilized for high-power ion heating and measurement of the ion temperature (T_i) profile by charge exchange spectroscopy. Significant progress was achieved in ion heating experiments using P-NB, and a high T_i of 5.2 keV was achieved at the plasma center. A T_i peak profile with a steep gradient in the core region was observed, indicating an improved mode of ion transport. The enhancement of toroidal flow in the core region was observed with the T_i rise. Transport analysis shows improvement in anomalous transport in the core region, and the neoclassical transport remains unchanged when the high T_i is realized.

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

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1. Introduction

Ion temperature is one of the most important parameters for realizing a continuous fusion reaction in magnetically confined fusion plasmas. In particular, realization of improved modes with transport barriers such as internal transport barriers (ITB) and edge transport barriers (ETB) is necessary for high-performance plasma confinement. Improved ion transport was observed not only in tokamaks [1–3] but also in helical devices [4, 5]. The formation of a steep T_i gradient was observed in the outer region of electron-ITB/core electron-root confinement (CERC) in the Compact Helical System (CHS) [6]. The mechanism of, and the necessary conditions for, the improvement of ion transport in helical systems are not yet fully understood; thus, the study of improved ion confinement is currently one of the most important issues in helical devices.

Before the 9th experimental campaign of the Large Helical Device (LHD), ion heating experiments were performed by tangential neutral beam (NB) injection [7]. There are three beam injectors of negative-ion-based NB with a very high beam energy of 180 keV, which are the main heating devices in LHD, and the total port-through beam power was over 14 MW [8]. However, such beams with energies considerably greater than the critical energy ($E_c \sim 120$ keV for plasmas with $T_e \sim 4$ keV) mainly heat electrons in the target plasmas, resulting in a relatively low ion heating power [9], as shown in Fig. 1. In order to increase the net ion-heating power per ion, the ion heating experiments were performed in a high-Z discharge, in which the ion population is much lower than that of the low-Z plasmas. In LHD a high T_i of 13.5 keV was realized with Argon gas puffing. Although the experiments were performed in a high-Z plasma because of the low ion heating power, the achievement shows the high potential of high-T_i plasma confinement in a helical configuration [7, 10].

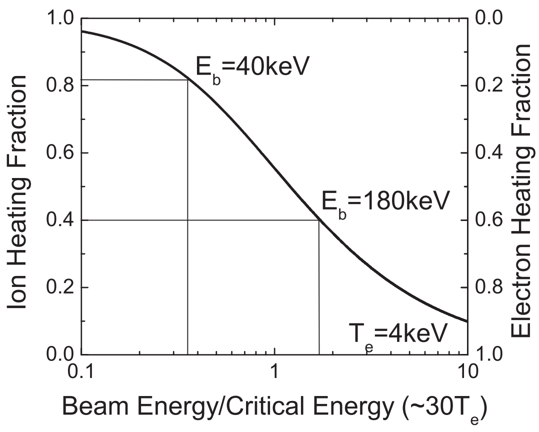

Fig. 1 The ion/electron heating fraction of NB power as a function of beam energy.

The next step is the production of high-T_i plasmas in low-Z discharges. For this purpose, a perpendicular NB (P-NB) with a low beam energy of 40 keV was installed

author's e-mail: nagaoka@LHD.nifs.ac.jp

in LHD in the 9th experimental campaign [11]. The NB has a high ion-heating efficiency of 80 % for plasmas with T_e = 4 keV (see Fig. 1) [9], and the direct ion heating power was significantly increased in LHD experiments.

P-NB can be utilized for profile measurement of T_i by charge exchange spectroscopy (CXS); thus, ion heat transport can be estimated experimentally [12]. Moreover, P-NB has a high particle fueling rate due to a large beam current of 150 A, and it is also utilized for particle fueling and controlling the density profile. In this paper, we present recent results of the high-T_i experiments using P-NB in LHD, in particular, the improved mode of ion transport. Beam fueling properties, the density profile dependence of T_i, ion transport property, and toroidal flow associated with high-T_i are also discussed.

2. Experimental Conditions

LHD is the world's largest helical device with a superconducting coil system. The major and averaged minor radii are 3.9 m and 0.6 m, respectively. The toroidal and poloidal periods are n = 10 and m = 2, respectively [13]. The plasmas are heated by electron cyclotron resonance heating (ECH) of 2 MW, ion cyclotron heating (ICH) of 2 MW, and three tangential negative-ion-based NBIs with a total port-through power of 14 MW (BL1-3). A perpendicular NBI with the low energy of 40 keV was installed in the 5-O port (outboard side port in a horizontally elongated cross-section) of LHD in 2005, which is called BL4. Four positive-ion sources were mounted on the beam injector, and the total port-through power was upgraded to 6 MW in 2006. Two power supply systems (BL4-A and BL4-B) can independently control the beam operation parameters such as pulse timing, beam energy, and beam duration. The nominal pulse duration is 10 sec, and the beam species is hydrogen. Beam injection with a total port-through power of 7 MW was achieved in the 10th experimental campaign [11].

Two systems of active CXS were applied to the P-NB as a probe beam. One is a toroidal system having toroidal lines of sight, which can measure the profiles of T_i and toroidal rotation of the plasma. The other is a poloidal system having poloidal lines of sight, which can measure the profiles of T_i and poloidal rotation of the plasma. Half of the P-NB (BL4-A or BL4-B) is modulated (ON for 100 msec and OFF for 100 msec) for CXS measurement to acquire the background signal [12].

3. Results and Discussions

A high-current beam with low energy has a large particle fueling rate. In order to investigate the beam fueling of the P-NB, the beam current scan was performed by changing the number of operating ion sources with the same gas condition in the inward-shifted magnetic configuration of R_{ax} = 3.60 m, in which the confinement of fast ions is better than that of outward-shifted configurations of LHD [13]. The target plasma has a low density of 0.7×10^{19} m^{-3} and is sustained by a tangential NB with a low port-through power of 3.7 MW in the present experiment. The electron temperature (T_e) and T_i of this plasma are 2.5 and 1.4 keV, respectively. The electron density increases with beam current during beam injection, which is shown in Fig. 2 (a), and an increase rate of 3×10^{16} m^{-3}s^{-1}A^{-1} (2.3×10^{20} s^{-1}MW^{-1}) was obtained. The electron density has a flat profile and the profile of density increase rate is shown in Fig. 2 (b). The density increase rate also has a flat profile. The beam fueling calculated by the FIT code [14] is consistent with the experimental results, and is also shown in Fig. 2 (b). This result indicates that the density increases due to beam fueling in the plasmas mainly heated by P-NB, while the density tends to decrease in the plasmas mainly heated by tangential NBs because of the pumping-out effect of hot electron plasmas.

The ion heating experiments using P-NB were performed with the inward-shifted magnetic configuration of 3.55 m ≤ R_{ax} ≤ 3.70 m, because the heating efficiency of P-NB of inward-shifted configurations is better than that of outward-shifted ones [13]. The P-NB power dependence of T_i was investigated in the plasmas heated by P-

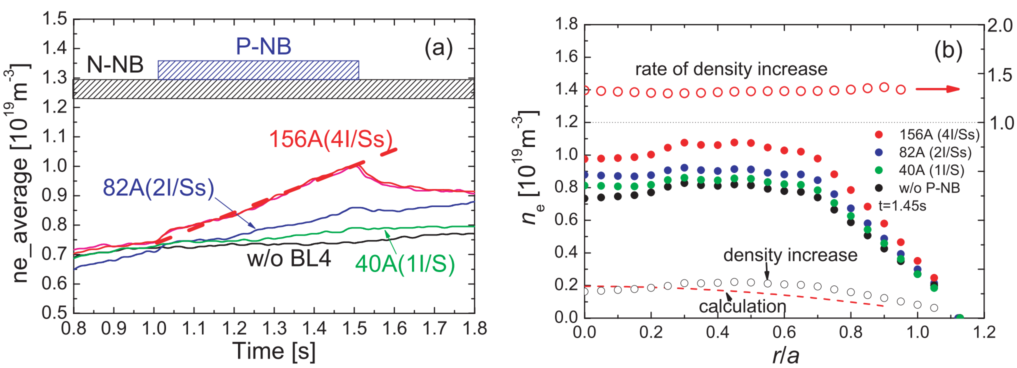

Fig. 2 (a) The response of line -averaged electron density to P-NB injections. (b) The density profiles with P-NB injections of 0 A, 40 A, 82 A, and 156 A. The profile of density increase rate is shown in the upper region. The beam fueling calculated by the FIT code (dashed red line) and the density increase observed experimentally (open circles) are also shown in the bottom region.

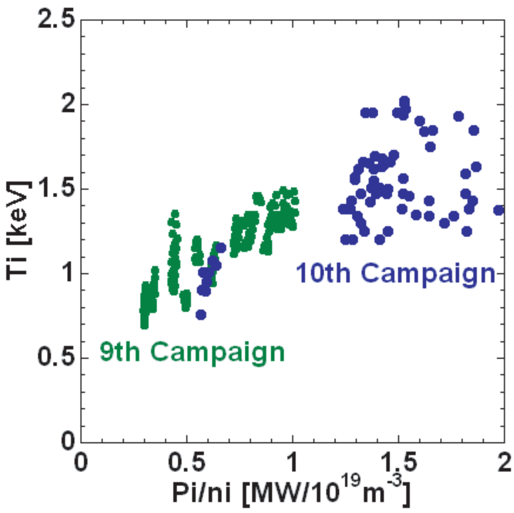

Fig. 3 Central T_i as a function of ion heating power per an ion.

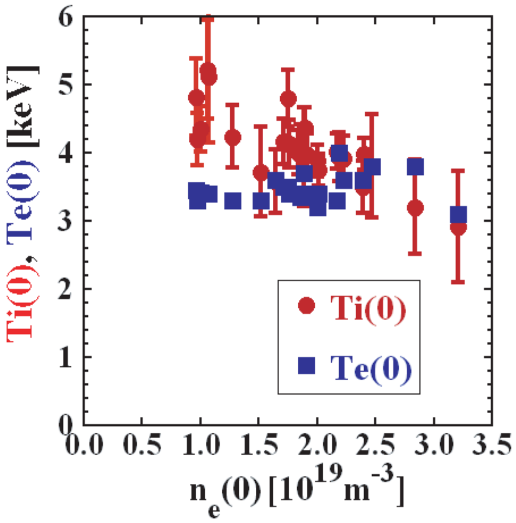

Fig. 4 Central T_i as a function of central electron density. Central T_e at the same time is also shown.

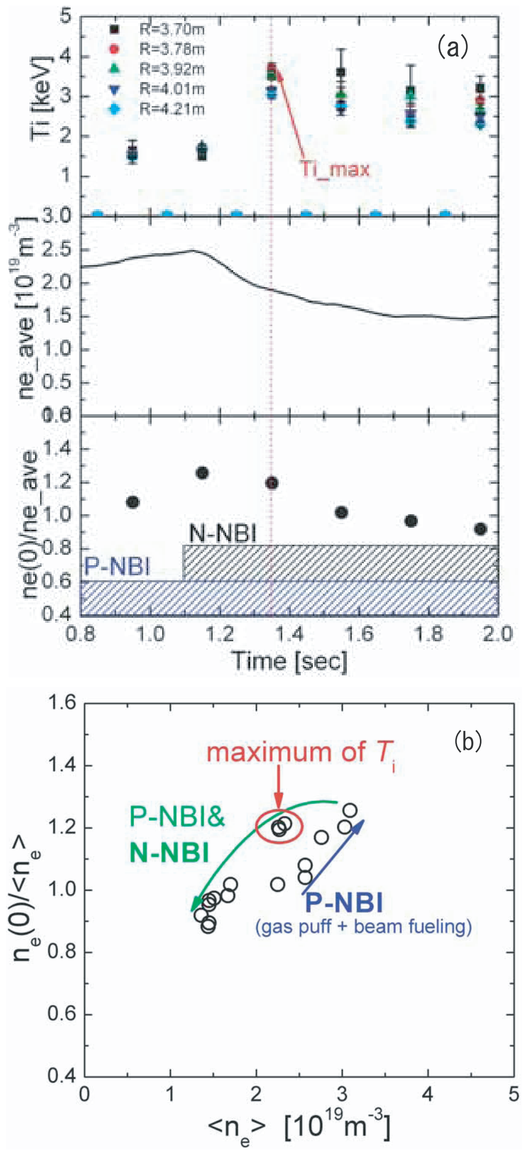

Fig. 5 (a) The T_i (upper), line-averaged electron density (middle), and a peaking factor (bottom). The beam injection pattern is also shown at the bottom figure. (b) The peaking factor as a function of averaged density. The trend is shown by arrows.

NB alone. The maximum T_i of each discharge is plotted in Fig. 3 as a function of ion heating power normalized by the ion density. In this figure, it is clearly seen that T_i increases with ion heating power. In the case of the combination of P-NB and tangential NB heating, T_i also depends on P-NB power. It is noted that the heating power dependence of T_i shown in Fig. 3 continuously connects to the higher heating power region obtained in high-Z experiments, which supports the extension of these results obtained by the high-Z discharges to the low-Z plasmas [7].

Plasmas with T_i higher than T_e were obtained after superimposition of tangential NBs over the P-NB heated plasma, although T_e tends to be higher than T_i in LHD because of the high electron heating power of tangential NBs. The central T_i of 5.2 keV was achieved with the central electron density of $1.2 \times 10^{19}\,\mathrm{m}^{-3}$. The high-$T_i$ regime was extended toward high-density plasmas, and the central T_i of 3 keV was achieved with the central electron density of $3.2 \times 10^{19}\,\mathrm{m}^{-3}$, which is shown in Fig. 4. The central T_e is lower than T_i in the low-density region, indicating the occurrence of selective ion heating. T_e and T_i are almost same in the high-density region. This is considered to be attributable to short equi-partition time in the high-density regime.

The highest T_i of the discharge was realized in the density decay phase after superimposition of tangential NBs. The time trace of T_i, the line-averaged electron density, and the central density divided by the line averaged density as a density peaking factor are shown in Fig. 5 (a). After superimposition of tangential NB heating ($t = 1.1$ sec), the electron density decreases and T_i increases, subsequently reaching the maximum value at

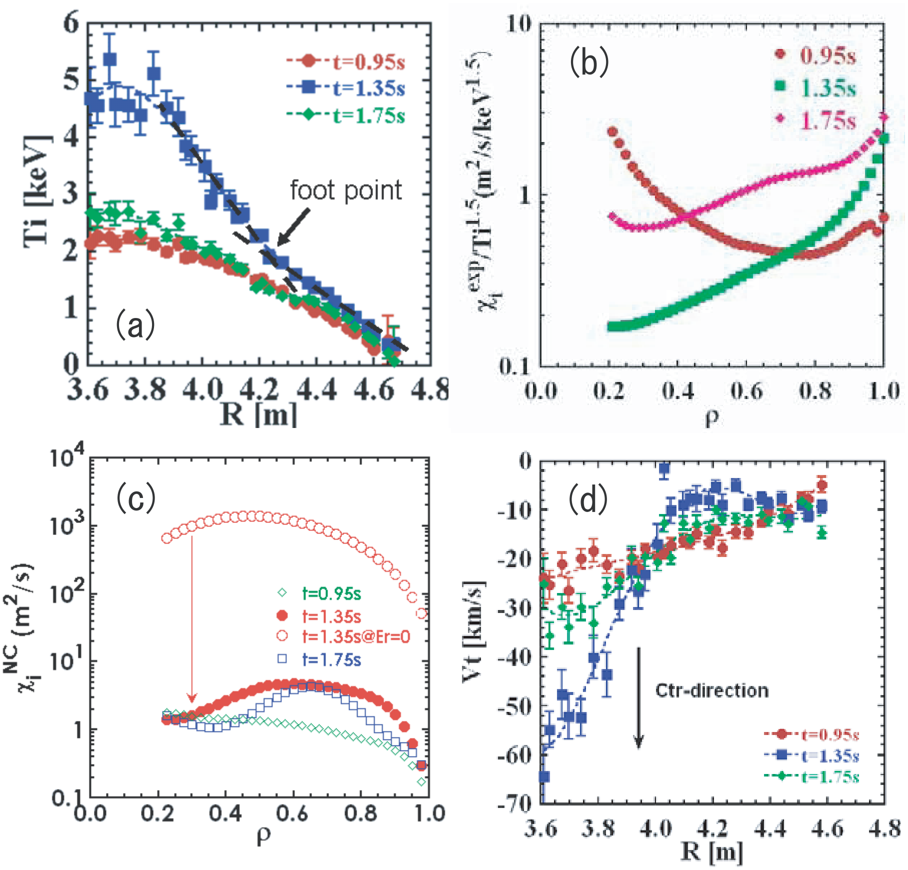

Fig. 6 (a) The T_i profiles of the plasma heated by P-NB alone (t = 0.95 sec), in the high-T_i phase after superimposition of N-NB (t = 1.35 sec), and mainly heated by N-NB (t = 1.75 sec). (b) The experimental ion thermal diffusivity. (c) The neoclassical ion-thermal diffusivity w/ and w/o neoclassical ambipolar radial electric field. (d) The toroidal rotation profile.

t = 1.35 sec. Further, T_i begins to decrease gradually while the electron density continues to decrease. The peaking factor increases in the P-NB heating phase and decreases after superimposition of tangential NBs. This is a general tendency in LHD plasmas; the density profile becomes a peaked one in P-NB heating plasmas and a flat or hollow one in tangential NBs. The peaking factor of the electron density still maintains a high value when T_i reaches its maximum, while the electron density decreases quickly (Fig. 5 (b)). Therefore, it seems that the peaking factor of the electron density is important for the T_i rise, and that the peaked density profile is preferable for realization of a high T_i.

Figure 6 (a) shows the T_i profiles at the P-NB phase (t = 0.95 sec), the maximum T_i phase (t = 1.35 sec), and after the decrease in T_i with decrease in NB power (t = 1.75 sec). T_i has a peaked profile and a steep gradient is formed in the core region of R < 4.25 m when T_i becomes high. T_e is 4 keV at the center and is almost the same as the T_i at R > 4.25 m when t = 1.35 sec. The central T_i strongly depends on the T_i gradient in the core region of R < 4.25 m, indicating the improvement of ion heat transport in this region. The position of the foot point, in which the gradient of T_i changes slightly, moves depending on some parameters. The T_i gradient inside the foot point significantly changes depending on the ion heating power. However the dependences of the foot position and the temperature gradient are not obtained in detail and further investigation is necessary.

The ion thermal diffusivity was analyzed and the experimental ion diffusivities normalized by the gyro-Bohm factor in the three time slices; (the only P-NB heating phase, the highest T_i phase, and the phase after the decrease in T_i) are shown in Fig 6 (b). The ion diffusivity in the high-T_i phase is significantly reduced in the core region. The neoclassical transport was calculated by the GSRAKE code [15]. The radial electric field is provided by the ambipolar condition and is negative (ion-root) in the core region [16]. The experimental observation of radial electric field or the poloidal rotation is difficult in the high-T_i phase because of a hollow carbon impurity profile (discussed later). However, the neoclassical radial electric field is considered to be a good indication in LHD plasmas, as demonstrated in previous studies [17, 18]. The neoclassical ion thermal diffusivity does not change in the core region, as shown in Fig. 6 (c), while T_i increases more than twice [16]. In such a low-collisionality regime, the neoclassical ion heat flux without the electric field is predicted to depend strongly on $T_i^{9/2}$. The temperature degradation of the neoclassical ion transport is considered to be significantly suppressed by the negative radial electric field.

The toroidal flow profile was measured by the toroidal CXS system. A large toroidal flow with a velocity of 60 km/sec was generated in the core region when the high T_i was realized, as shown in Fig. 6 (d). The flow direction is consistent with the predominant direction of tangentially injected NBs. These observations indicate a strong correlation between ion diffusivity and parallel viscosity. It is noted that large toroidal flows associated with high T_i are also observed in tokamak devices [19]; thus, the comparison of large flow production in high-T_i plasmas between helical and tokamak devices is an interesting subject [12]. The poloidal rotation in the core region cannot be observed when the T_i becomes high, because the carbon impurity has a strongly hollow profile associated with the T_i rise. This "impurity hole" also shows strong correlation with the T_i rise. The outward flow of carbon impurity against the negative gradient of carbon density was also observed [20]. The large error bars of T_i in the core region with t = 1.35 sec in Fig. 6 (a) are attributable to the formation of the impurity hole. Although the impurity pumping-out effect can be expected in electron-root plasmas according to the neoclassical theory, the understanding of impurity hole formation in the neoclassical ion-root is a new subject related to the high-T_i experiments in helical devices.

4. Conclusion

The installation of P-NB injection resulted in significant progress in high-T_i experiments in LHD: (1) an upgraded power of direct ion heating and (2) profile measurements of T_i, toroidal and poloidal flows, and carbon impurity. An improved mode of ion transport was realized in the core region and a central T_i higher than 5 keV was achieved. The high-T_i plasma was extended toward the high-density regime. A large toroidal flow and an impurity hole were observed in the core region associated with the T_i rise. A negative radial electric field (neoclassical ion-root) significantly suppresses the degradation of ion thermal diffusivity, and a reduction in anomalous transport was observed in the core region. These are preliminary results and not yet fully understood. Systematic experimental studies and neoclassical viscosity analysis are in progress.

Acknowledgements

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