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High-Energy and High-Power NBI Heating Experiments in LHD

Y. Takeiri, M. Osakabe, K. Ikeda, O. Kaneko, K. Tsumori, Y. Oka, K. Nagaoka, T. Shimozuma, S. Kubo, S. Morita, M. Yokoyama, H. Funaba, S. Murakami, J. Miyazawa, K. Narihara, H. Idei, Y. Yoshimura, T. Notake, M. Goto, S. Inagaki, S. Masuzaki, S. Muto, Y. Nagayama, B. J. Peterson, K. Tanaka, K.Y. Watanabe, K. Ohkubo, T. Mutoh, H. Yamada, A. Komori, K. Ida, Y. Nakamura, K. Kawahata, N. Ohyabu, K. Matsuoka, O. Motojima, and LHD Experimental Group

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

1. Introduction

Achievement of high-temperature plasmas is one of the main goals in the Large Helical Device (LHD), which is the world-largest superconducting helical system. The LHD is equipped with a negative-ion-based neutral beam injection (NBI) system as a main heating device, and the plasma electrons are dominantly heated due to its high injection energy of more than 150 keV (H). Thus, the ion temperature had been below 2.5 keV and lower than the electron temperature. A simple approach to raise the ion temperature is to increase the ion heating power by some means. Another approach, which is more important, is to improve the ion transport by achievement of the neoclassical electron root generating a strong positive electric field. In the 2001 experimental campaign, the third injector was newly installed and the NBI power was much increased, resulting in achievement of a high ion temperature of 5 keV with use of neon gas-puffing. By superimposing the centrally focused intense ECRH microwave on the NB-heated plasma, an internal transport barrier (ITB) was observed in the electron temperature profile, which suggests a formation of the neoclassical electron root. In the followings, the experimental results of high temperature plasmas are presented with transport analyses.

2. Negative-NBI System and ECRH System

The LHD-NBI system was designed for achievement of high-$n\tau T$ plasmas, where the target density is relatively high, more than $3\times10^{19}m^{-3}$ [1,2]. The nominal injection energy is as high as 180 keV for the tangential hydrogen injection. Two negative-ion-based NB-injectors of co- and counter-injection were operational in 1998, and one more counter-injector was installed in 2001. The total injection power was increased to 9 MW with a hydrogen beam energy of around 160 keV. The LHD-ECRH system employs two 82.7GHz, two 84 GHz and three 168 GHz gyrotrons, and each microwave is injected into the LHD as a strongly focused Gaussian beam using the vertical and horizontal antenna systems. A high-power ECRH up to 1.8 MW was concentrated within an averaged minor radius of ρ=0.2 in an inner magnetic-axis configuration of R_{axis} < 3.53 m [3].

3. Achievement of High Ion Temperature with Neon Injection

Since the injection energy is so high that the electron heating power would be dominant, the effective ion heating power should be enhanced to raise the ion temperature. In order to increase the plasma absorption power of the high-energy neutral beams in low-density plasmas, neon gas was injected, instead of hydrogen or helium gas. Figure 1 shows the comparison of the neon-injected plasma with the hydrogen one in R_{axis}=3.53m. Although the port-through NBI power is almost the same, around 8 MW, in both cases, the ionized beam power (plasma absorption power), estimated from the shine-through power measurement [4], is about 1.3 times larger in the neon plasma at t=1.0sec (n_e=1x10^{19}m^{-3}). The ion temperature in the neon plasma is higher by about 1 keV than that in the hydrogen plasma. Figure 2 shows the central ion temperature as a function of the plasma absorption power normalized by the line-averaged electron density for both neon and hydrogen plasmas in R_{axis}=3.6m. Since the Z_{eff} of the neon plasmas is higher, the beam ionization rate is 1.5 – 2 times larger than that in the hydrogen plasmas for low-density target plasmas below 1x10^{19} m^{-3} in R_{axis}=3.6 m. From the comparison of the beam ionization rates between the neon and the hydrogen plasmas, the Z_{eff} of the neon plasmas is roughly estimated to be 2 times larger than that of the hydrogen plasmas. Assuming that the Z_{eff} of the hydrogen plasmas is around 3, the ion density of the neon plasmas is nearly a half of that of the hydrogen plasmas. Since the electron temperature is not so different, the effective ion heating power rate is double for the neon plasmas. As shown in Fig. 2, the ion temperature in the neon plasmas is increased linearly to the normalized absorption power and reaches 5 keV, while it is lower and is saturated in higher powers in the hydrogen plasmas. Although the effect of the neon gas injection can be explained by the increase in the absorption power and the enhancement of the direct ion heating power with a reduced number of ions, there could be a possibility of improvement of the plasma confinement by the impurity injection.

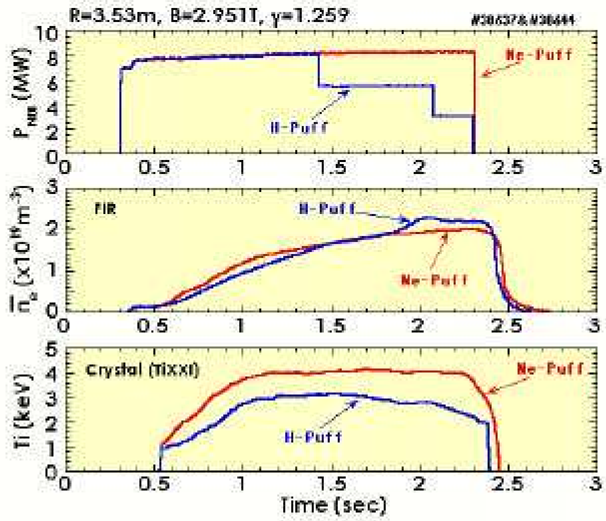

Fig. 1 Time evolution of the plasma parameters for the neon and the hydrogen discharges.

The transport analyses of the neon plasmas show that the electron transport is not largely changed compared with the hydrogen or helium plasmas. On the other hand, the ion transport cannot be locally analyzed as the ion temperature profile is not measured. The collisionality of neon ions is large and in the plateau regime because the ion collisionality depends on Z^3. The ion thermal diffusivity, roughly estimated by assuming that the ion temperature profile is parabolic, is 2 – 5 m^2/s in the neon plasmas, and is nearly the same as or a little bit larger than that in the hydrogen plasmas the collisionality of which is smaller by 1 – 2 orders of magnitude. The linear increase of the ion temperature in the neon plasma could be ascribed to the neon ions in the collisional

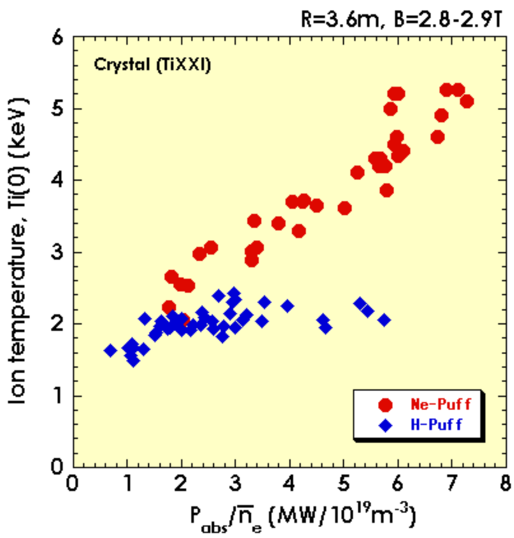

Fig. 2 Central ion temperature as a function of the plasma absorption power normalized by the electron density for the neon and the hydrogen plasmas.

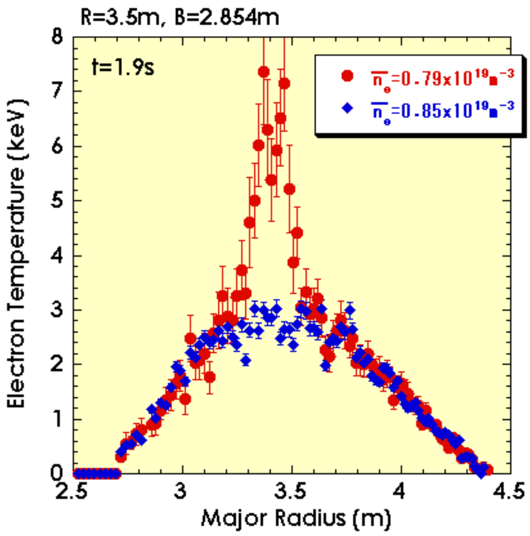

Fig. 3 Electron temperature profiles with and without ITB.

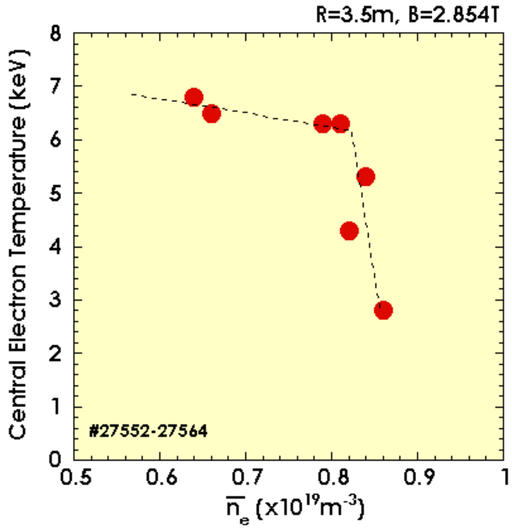

Fig. 4 Central electron temperature as a function of the electron density.

plateau regime, while the hydrogen ions in the collisionless $1/\nu$ regime could lead to the saturation of the ion temperature in the hydrogen plasma.

4. Formation of Electron Internal Transport Barrier

In the experiments where the centrally focused intense ECRH microwave was superimposed on the NB-heated plasma, the electron temperature shows a centrally peaked profile with a steep gradient inside ρ=0.3 – 0.4. An example of this electron ITB (internal transport barrier) profile is shown in Fig. 3. The central electron temperature exceeds 10 keV in a lower density. There exist various kinds of threshold for the electron ITB formation, such as the ECRH power, the NBI power, and the density. Figure 4 shows the central electron temperature as a function of the line-averaged electron density, and the electron temperature profiles with and without ITB are shown in Fig. 3 at around the threshold densities. The electron transport is much improved in a region of the ITB formation. Figure 5 shows the electron thermal diffusivity χ_e as a function of the collisionality normalized by $\nu_{eq} = \varepsilon_h^{3/2}\, v_T\, \iota\, M/2\pi R$ at ρ=0.2 in the case of the ITB formation with an ECRH power threshold at n_e=0.3x10^{19}m^{-3}. When a small ECRH power (180kW) is added to the NBI plasma, the T_e at ρ=0.2 is increased a little and the χ_e is much increased. With a larger ECRH power (280kW) the electron ITB profile is formed and the T_e at ρ=0.2 is raised, and then the χ_e is much reduced. The reduction of the χ_e at the threshold suggests the transition of neoclassical ion root to electron root. At this transition a strong positive radial electric field of around 50 kV/m is generated in the theoretical ambipolar flux calculation [5], although the electric field is not measured. However, the χ_e in the ITB profile is one-order of magnitude larger than the theoretical one in the neoclassical electron root, as shown in Fig. 5. The experimentally observed χ_e reduction in the ITB formation could be attributed to the suppression of the anomalous transport due to the electric field shear at a boundary of the ITB formed by the transition of the electric field [6].

Figure 6 shows a $T_e - n_e$ diagram for both ITB and no-ITB profiles at ρ=0.2. In the figure, the local ITB formation at ρ=0.2 is judged by the gradient of T_e, $dT_e/d\rho$, at ρ=0.2, i.e., no ITB formation for $dT_e/d\rho<1$, ITB formation for $dT_e/d\rho>5$, and marginal ITB formation

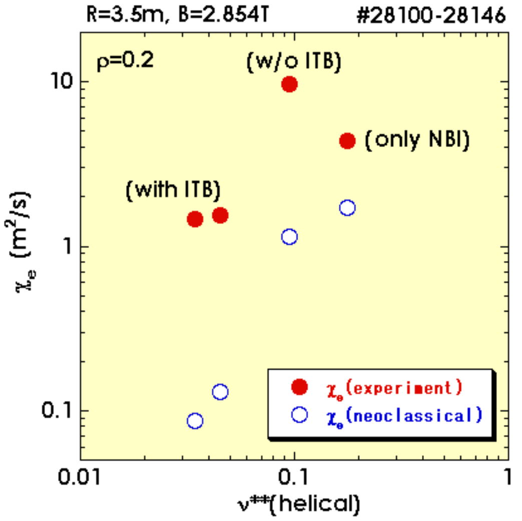

Fig. 5 Electron thermal diffusivity as a function of the collisionality.

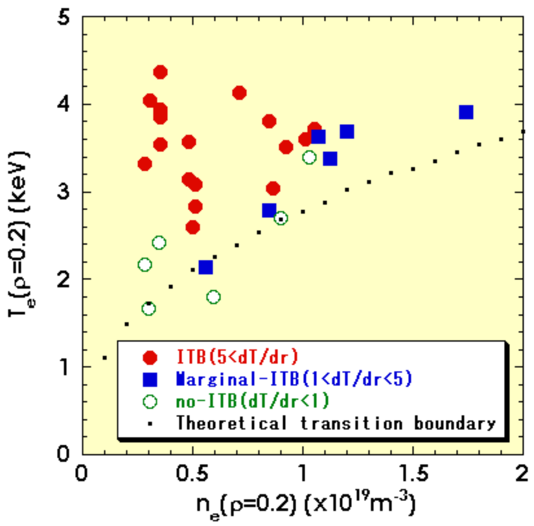

Fig. 6 T_e – n_e diagram for both ITB and no-ITB profiles at ρ=0.2.

for $1 < dT_e/d\rho < 5$. In the figure, the theoretical transition boundary to the electron root from the ion root is also indicated. As shown in Fig. 6, the temperature threshold for the ITB formation is dependent on $n_e^{0.4}$, which coincides with the theoretical prediction. The electron ITB profile is also observed in relatively high-density plasmas of $>1\times10^{19}m^{-3}$ with a higher ECRH power and a higher NBI power. Even in the neon plasmas the marginal ITB formation is observed at $n_e=1.8\times10^{19}m^{-3}$ in the ECRH injection into a plasma heated by 8MW-NBI. Although a clear increase in the ion temperature has not been recognized, a high electron temperature in the ITB formation would enhance the ion heating ratio in high-power NBI heating, leading to increase in the ion temperature. Moreover, the neoclassical electron root in the ITB formation would reduce the ion transport in the collisionless regime, which would realize a higher ion temperature.

5. Summary

To raise the ion temperature with a high-energy negative-NBI heating, neon gas was injected for increasing the plasma absorption power of the neutral beam and enhancing the effective ion heating power with a reduction of the ion number in high-Z_{eff} plasmas. As a result, the ion temperature is raised to 5 keV at an NB-injection power of 8 MW. By injection of centrally focused ECRH microwave into the NBI-heated plasma, the electron ITB profile with a steep gradient inside ρ=0.4 was observed. The temperature threshold for the ITB formation depends on $n_e^{0.4}$, which agrees with the theoretically predicted transition to the neoclassical electron root from ion root. The electron ITB was observed also in the neon plasmas. It is important to obtain a high ion temperature by achieving the improvement of the ion transport in the neoclassical electron root, and this is a future work.

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