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LHDにおける高イオン温度をめざしたプラズマ研究の進展
Progress of high ion-temperature plasma research in Large Helical Device

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Steady state operation of high temperature and high density plasmas is required for realizing a nuclear fusion reactor. Significant advantage of helical plasmas for steady state operation has been confirmed in the Large Helical Device (LHD). High density plasmas in helical plasmas, in general, show good confinement properties, and the high-density operation scenario was proposed for helical reactors. On the other hand, production of high-ion temperature plasmas has been remained as a subject to be solved in the LHD experiment.

In the initial stage of the LHD project, negative-ion-based neutral beam injectors (NBI), which had been out of practical use at that time, were developed and installed in LHD with the tangential beam injection geometry, because perpendicular fast ion confinement had not been understood yet. The tangential NBIs with the energy of up to 180keV were very effective to high-power plasma heating and significantly contributed to high performance plasma production in LHD, in particular, in high β and high density plasma regime [1-2]. The high-ion temperature plasma, however, was not realized with the tangential NBIs, because such high energy ions mainly heat electrons.

The demonstration of high-power ion heating with the tangential NBIs was performed in low density and high-Z conditions. The central ion temperature of 13.5keV was achieved in an argon seeded plasma [3]. It is noted that the capability of high-ion temperature plasma confinement in helical plasmas was experimentally confirmed in this simulation experiment with the high-Z condition.

In order to investigate the possibility of plasma heating with perpendicular fast ions, confinement characteristics of the ripple-trapped fast ions were intensively studied. It was theoretically and experimentally found that the perpendicular fast ions are well confined and effectively heat plasmas in the inward shifted configurations in LHD [4-5]. Then, for high-power ion heating experiments, large positive ion sources with a low-beam energy of 40kV and a high-neutral beam current of 75A were developed, and the perpendicular NBI was installed in LHD. Effective plasma heating with the perpendicular NBI was confirmed, and the high-ion temperature regime in helical plasmas was significantly extended [6]. The central ion temperature of 7.3keV was achieved with the combination of tangential and perpendicular NBIs in the 16th LHD experiment campaign in FY2012.

The characteristics of high-ion temperature plasmas have been experimentally investigated, and some preferable features required for the core plasma in the fusion reactor have been identified [7]. Here, we discuss on the improvement of ion heat transport and the impurity hole formation in a core region of high-ion temperature plasmas.

As an increase in the ion heating power with the perpendicular NBI, the ion temperature gradient becomes steep in the core region, and the ion internal transport barrier (ion ITB) is formed. Figure 1 shows the profiles of the typical plasma with the ion ITB formation caused by the carbon pellet injection. The ion temperature in the core region is much higher than the electron temperature, while they are almost identical near the edge region. The ion thermal diffusivity significantly decreases in the ion ITB core region and reaches a neoclassical transport level. The radial electric field in the core region was measured with the heavy ion beam probe (HIBP), and it was observed that a weakly negative field in the L-mode phase becomes a deeper negative one at the transition to the ITB phase. This is consistent with the prediction by the neoclassical ambipolarity. The improved confinement in the ion ITB is attributed to reduction of the turbulent transport without the bifurcation of radial electric field [6].

A transition of the impurity convection was identified during the formation of ion ITB [8]. As shown in Fig. 2, the carbon density suddenly starts to decrease when the ion temperature gradient exceeds a critical value. On the other hand, the carbon density increases with a lower-ion temperature gradient than the critical value [9]. The outward convection of impurities is stronger in heavier impurities. As a result, the impurity-free plasma (impurity hole) is realized in the core plasma with the ion ITB. It is noted that the improved heat transport and the impurity exhaustion are simultaneously realized in helical plasmas, while the impurity accumulation in the improved confinement regime remains as a subject to be solved in tokamaks. The physical mechanism of impurity hole formation is under investigation.

The high-ion temperature plasmas heated by the tangential and perpendicular NBIs have very promising features on the MHD stability as well as the impurity transport. No disruptive phenomenon has been observed in the ion ITB plasmas so far. Recently, the understandings of the high-ion temperature plasma characteristics have significantly progressed, such as the charge-exchange loss channel, the impurity effect on transport improvement [10-11], and the transition of ion thermal transport [12]. The discharge cleaning technique with the ion cyclotron range of frequency heating is very effective to realize the high-ion temperature plasmas with suppression of the particle recycling at the wall. Prospects for the deuterium experiment planed in LHD will also be discussed.

[1] Y. Takeiri, et al., Fusion Sci. Tech., **58**, 482 (2010).
[2] O. Kaneko, et al., Nucl. Fusion, **53**, 104015 (2013).
[3] Y. Takeiri, et al., Nucl. Fusion, **45**, 565 (2005).
[4] S. Murakami, et al., Fusion Sci. Tech., **46**, 241 (2004).
[5] M. Osakabe, et al., Fusion Sci. Tech., **58**, 131 (2008).
[6] K. Nagaoka, et al., Nucl. Fusion, **51**, 083022 (2010).
[7] 永岡賢一、他、プラ核学会誌、**86**, 69 (2010).
[8] K. Ida, et al., Phys. Plasmas, **16**, 056111, (2009).
[9] M. Yoshinuma, et al., H-mode workshop, 2013.
[10] M. Osakabe, et al., 12th Asia Pacific Phys. Conference 2013.
[11] S. Murakami, et al., Joint 19th ISHW and 16th IEA-RFP workshop, Padova, 2013.
[12] H. Nakano, et al., 12th Asia Pacific Phys. Conference 2013.

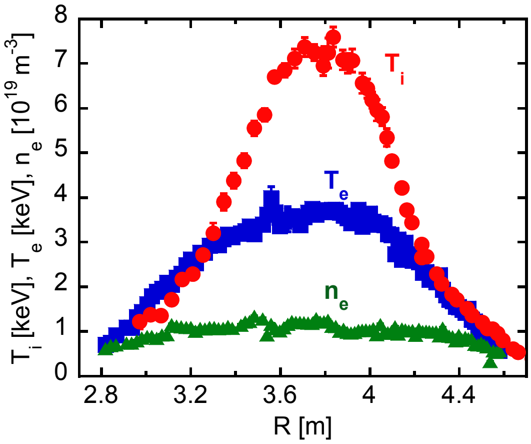

Fig.1 Profiles of the ion temperature, the electron temperature and the electron density of the typical ion ITB plasma heated by the NBI with the total power of 23 MW.

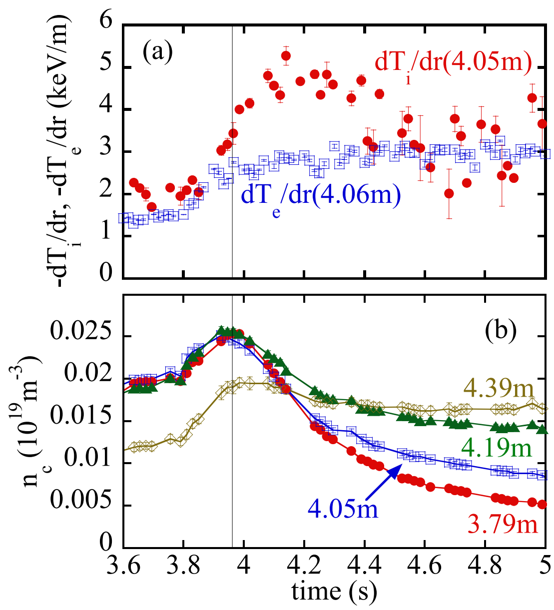

Fig.2 Time evolutions of (a) the temperature gradients and (b) the carbon density at different minor radii. The carbon density in the core significantly decreases in the ion ITB phase.