Parameter Regime of Ion Internal Transport Barrier Formation in the Large Helical Device

Kenichi NAGAOKA, Yasuhiko TAKEIRI, Katsumi IDA, Mikiro YOSHINUMA, Shigeru MORITA, Naoki TAMURA, Takeshi IDO, Akihiro SHIMIZU, Katsunori IKEDA, Masaki OSAKABE, Katsuyoshi TSUMORI, Haruhisa NAKANO and LHD Experiment Group

National Institute of Fusion Science, Toki 509-5292, Japan

(Received 8 December 2009 / Accepted 31 March 2010)

Improvement of ion heat transport was observed in the core plasma heated by neutral beam injection (NBI) in the Large Helical Device (LHD). A peaked ion temperature profile with a steep gradient (an ion internal transport barrier, ion ITB) formed in the plasma. To investigate the formation conditions of the ion ITB, a simple definition of ITB based on the reversal of the temperature gradient between the core and the edge is proposed. An ion ITB formed in the low-collisionality regime of $1/\nu$ with low density and high ion heating power in the LHD.

Keywords: ion heat transport, ion internal transport barrier, gradient reversal

DOI: 10.1585/pfr.5.S2029

1. Introduction

Recently, an ion internal transport barrier (ion ITB) was observed in the Large Helical Device (LHD) plasma heated by neutral beam injection (NBI). The ion temperature has a peaked profile with a steep gradient in the core region and becomes higher than the electron temperature at the plasma center. No transport barrier was observed in the electron temperature profile when the ion ITB formed. The ion thermal diffusivity in the plasma core decreased by a factor of three and reached the neoclassical level, where the negative radial electric field (ion root) is predicted by neoclassical ambipolarity [1–3].

The typical ion ITB formed after the superposition of additional NBI heating on the target plasma sustained by low-power NBI. The injection of a hydrogen or carbon pellet enhanced the ion temperature gradient. The squares in Fig. 1 show the ion temperature profile without ion ITB formation, and the circles show that with an ion ITB formed by superposition of NBI (t = 2.0 s) in the density decay phase after carbon pellet injection (t = 1.8 s). The slow down time of tangential NBI is about 0.3 s; thus, the effective heating power is still low at t = 2.06 s (see Fig. 1). The ion ITB can also form in gas puff discharges, but the ion temperature gradient is not as large. The direction of tangential NBI is not as sensitive for ion ITB formation, indicating that the plasma current direction is not as important. Understanding the mechanism of ion ITB formation is crucial for high-performance plasma confinement in stellarators. A conventional approach is to clarify the operation regime for ion ITB formation in the plasma.

To identify ion ITB formation from experimental data, a definition of the ion ITB is necessary. The term "ITB" was first used to refer to tokamak plasmas [4], and several types of ITB occur in tokamak plasmas depending on the discharge, such as a box-type ITB in reversed shear configurations and a weak ITB in positive shear configurations [5, 6]. There are two types of ITB definition. One is based on feature of the temperature profile such as temperature gradient or peaking factor. The other is based on transport properties such as the power dependence and temperature dependence of transport. The latter definition is much better than the former in a physical sense; however, it is not easy to identify the change in transport properties from the experimental data. On the other hand, the former is useful for easy identification of an ITB. A normalized temperature gradient R/L_T is often used for ITB definition when ITBs are compared between different devices, where R and L_T are the major radius of the

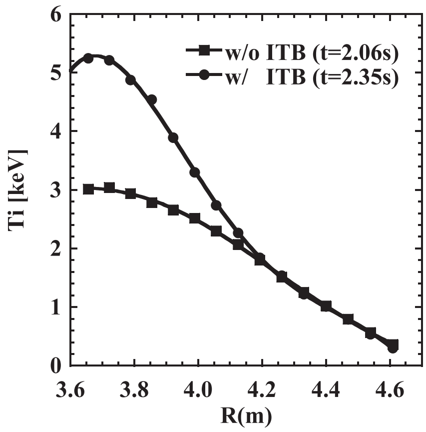

Fig. 1 Ion temperature profile of NBI-heated plasma with ITB (circles) and without ITB (squares).

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

plasma and the scale length of temperature gradient, respectively [7]. This definition is based on the so-called "critical gradient scale length model" of transport [8]. The threshold value of R/L_T, which determines whether an ITB forms, is not identical among devices [6]. It is not clear whether the critical gradient scale length model is applicable to helical plasmas and how the threshold value of R/L_T should be chosen for ITBs in helical plasmas. In this paper, an ITB definition based on the reversal of the temperature gradient in space is proposed and applied to ion ITB identification in the LHD. The operational regime of the ion ITB in the LHD is discussed.

2. Definition of ITB Based on Gradient Reversal in Space

Here we discuss the temperature profile and temperature gradient with and without a transport barrier, a schematic of which is shown in Fig. 2. First, an L-mode plasma without a transport barrier is considered. The temperature in the L-mode has a broad profile, and the temperature gradient in the core is weaker than that at the edge. This property is easily understood by a simple model. If the heat transport has the properties of Bohm diffusion or gyro-Bohm diffusion, the thermal diffusivity has a positive dependence on the temperature,

$$\chi_{\text{Bohm}} \propto T \quad \text{and} \quad \chi_{\text{gyro-Bohm}} \propto T^{3/2}, \tag{1}$$

where $\chi_{\text{Bohm}}, \chi_{\text{gyro-Bohm}}$ and T are the thermal diffusivities of Bohm and gyro-Bohm diffusion and the temperature, respectively. The property of gyro-Bohm diffusion is observed in LHD plasmas [9].

In the most simple transport model, the heat transport is given by

$$Q = -n\chi\nabla T, \tag{2}$$

where Q and n are the heat flux and density, respectively. If the heat flux normalized by the density is constant in the radial direction, the temperature gradient is inversely proportional to the thermal diffusivity,

$$\nabla T \propto \chi^{-1} \propto T^{-1} \ \text{ or } \ T^{-3/2}. \tag{3}$$

The practical heat flux normalized by the density is, of course, not a constant. Here we consider a simplified situation. The ion heating profile in low-density NBI plasma is peaked, and it may be reasonable to assume these condition. On the basis of Eqs. 1 and 3, the temperature gradient is understood to decrease with temperature. Thus, the temperature gradient in the core tends to be weaker than that at the edge:

$$|\nabla T(r_1)| < |\nabla T(r_2)| \quad \text{for } r_1 < r_2. \tag{4}$$

On the other hand, when a transport barrier forms, a steep temperature gradient is generated near the barrier. Here we introduce a new definition of an ITB as the formation of a larger temperature gradient in the core than at the periphery, that is,

$$|\nabla T(r_1)| > |\nabla T(r_2)| \quad \text{for } r_1 < r_2, \tag{5}$$

where r_1 and r_2 are located at the barrier region and outside the barrier, respectively. Equation 5 is useful for identifying ITB formation from experimental data. Figure 3 shows the ratio of the ion temperature gradient in the core (R = 4.0 m; $r/a \sim 0.42$) and that at the periphery (R = 4.4 m; $r/a \sim 0.88$). In the high-heating-power region, this ratio increases significantly with ion heating power, whereas it is almost constant in the low-heating regime where $P_i/n_i < 2 \times 10^{-19}$ MWm^3 (without an ion ITB).

In practical, the applicability of the present ITB definition is limited to plasma without a local heat source such

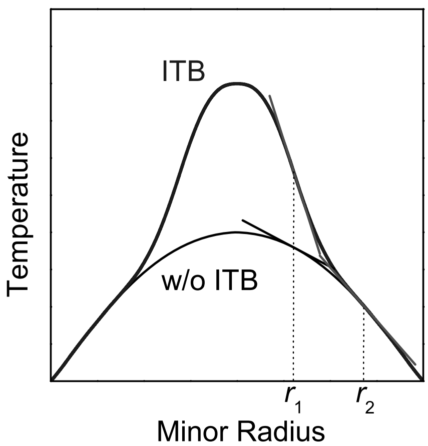

Fig. 2 Schematic of typical temperature profiles of ITB plasma and L-mode plasma. Temperature gradients in the ITB region (r_1) and peripheral region (r_2) are also shown.

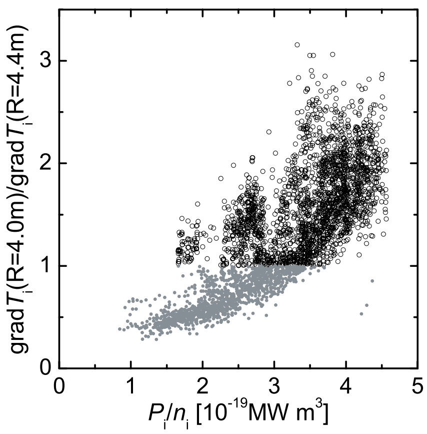

Fig. 3 Ratio of ion temperature gradient in the core (R = 4.0 m; normalized minor radius $r/a \sim 0.42$) and that at the periphery (R = 4.4 m; $r/a \sim 0.88$) as a function of total ion heating power normalized by the average ion density. Plasmas with and without an ion ITB are indicated by open (black) and closed (gray) circles, respectively.

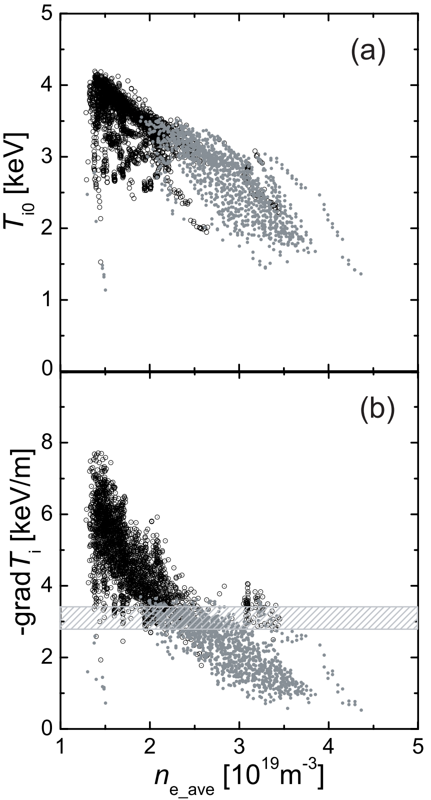

Fig. 4 (a) Central ion temperature and (b) temperature gradient at R = 4.0 m ($r/a \sim 0.42$) as a function of line-averaged electron density. Plasmas with and without an ion ITB are indicated by open (black) and closed (gray) circles, respectively.

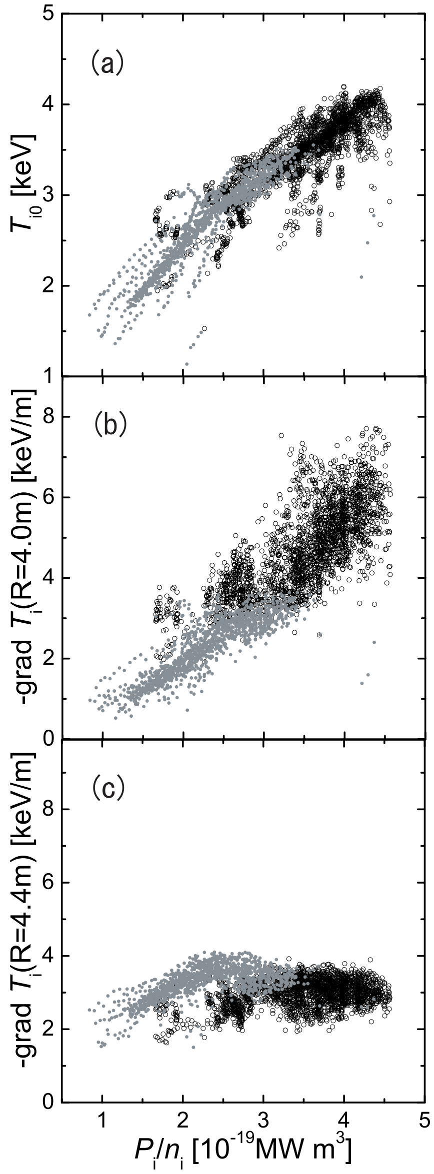

Fig. 5 (a) Central ion temperature, (b) gradient of ion temperature at R = 4.0 m ($r/a \sim 0.42$), and (c) that at R = 4.4 m ($r/a \sim 0.88$) as a function of ion heating power normalized by average ion density.

as centrally focused electron cyclotron resonance heating, because the change in transport properties is not clear in such cases from the temperature profile. A detailed analysis is required to identify an ITB when the assumption of constant heat flux normalized by ion density is not satisfied in a plasma.

3. ITB Formation Regime

We discuss here the plasma parameter regime of ion ITB formation using the ITB definition based on temperature gradient reversal introduced in the previous section. The magnetic axis was scanned in the range of 3.55 m $< R_{ax} <$ 3.75 m to explore high-ion-temperature plasma, and an ion ITB formed with all magnetic axis positions. The highest ion temperature plasma was obtained with R_{ax} = 3.60 m. The data analyzed here are limited to a magnetic configuration with a magnetic axis position of R_{ax} = 3.60 m and magnetic field strength of $B_t = -2.75$ T. (The polarity indicates the coil current direction, and the negative sign indicates that co-NBI is dominant.) This configuration is standard in LHD experiments. In other configurations, a parameter scan of density and heating power is not enough to see a clear parameter dependence of ion ITB formation.

The central ion temperature decreases monotonically with density, as shown in Fig. 4 (a), and a low-density plasma with a density of less than $n_{e\_ave} = 2.5 \times 10^{19}$ m^{-3} is favorable for ion ITB formation. The ion temperature gradient in Fig. 4 (b) shows the same feature. The gradient of ion temperature in the plasma core increases with decreasing density, and it is enhanced with ion ITB formation. Figure 4 (b) clearly shows that the identification of an ion ITB using the new ITB definition introduced in the previous section is almost the same as that using the critical temperature gradient.

The heating power normalized by ion density is useful for discussing the heating power dependence of the central ion temperature. Figure 5 shows the central ion tempera-

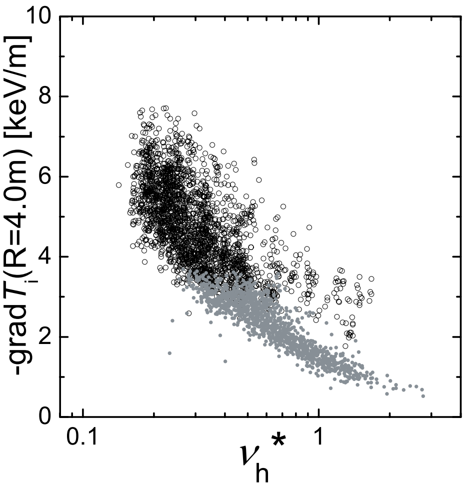

Fig. 6 Gradient of ion temperature at R = 4.0 m ($r/a \sim 0.42$) as a function of normalized ion collision frequency.

ture and ion temperature gradient in the core and peripheral regions as a function of total ion heating power normalized by average ion density. The ion temperature gradient in the core (R = 4.0 m) increases with normalized heating power and is enhanced in the high-power regime owing to ion ITB formation. The central ion temperature increases with normalized heating power; however, the dependence has a power of almost 0.5 and is weaker than that of the ion temperature gradient in the core region. The reason for the weak power dependence of the central ion temperature is considered to be the decrease in the ion temperature gradient in the peripheral region during ion ITB formation, which is shown in Fig. 5 (c). When the ion ITB formed, the gradient in the core became steep, but that in the periphery simultaneously decreased. This contrasting behavior of the ion temperature gradients in the core and peripheral plasmas implies a long-distance linkage of ion heat transport, which has attracted much attention in terms of non-local transport phenomena.

Finally, we discuss the collisionality. The ion ITB formed only in the low-collisionality regime. Figure 6 shows the temperature gradient of the ion ITB core plasma as a function of normalized ion collision frequency $\nu_h^* = \nu/\nu_{eq}$ where $\nu_{eq} = \varepsilon_{eff}^{3/2} v_{th}/(qR)$ is the collision frequency between the $1/\nu$ regime and the plateau regime. (Here, q is the safety factor and R is the major radius.) The ion ITB formed only in the $1/\nu$ regime, where the transport of helically trapped ions dominates the neoclassical transport. The neoclassical diffusion coefficient in the $1/\nu$ regime increases with decreasing collisionality. The experimentally observed temperature gradient has an anti-neoclassical transport property, indicating that the anomalous transport decreases with decreasing collisionality. The reduction in ion thermal diffusivity seems to saturate at the neoclassical level [1], and no disruptive phenomena were observed in the ion ITB in the LHD so far. The optimization of ripple transport of helically trapped particles may be a control knob for ion ITB behavior.

4. Conclusion

A definition of an ITB based on a temperature gradient reversal in space was proposed to identify ion ITB formation in NBI-heated plasmas in the LHD. The ITB definition may be useful in plasmas without a local heat source, and it is almost identical to the tokamak ITB definition based on a temperature gradient threshold.

The density, heating power and collisionality dependence of ion ITB formation were examined in NBI-heated plasma in the LHD. A low density of less than 2.5×10^{19} m^{-3} is favorable for ion ITB formation. A high ion heating power is required, and the dependence on the ion heating power normalized by the ion density is significant. The formation of an ion ITB is observed in the low-collisional regime of $1/\nu$, where helical ripple transport dominates the neoclassical transport. In this low-collisional regime, a significant improvement in neoclassical transport with a positive radial electric field (neoclassical electron root) is predicted at higher temperatures [10]. From these results, we conclude that extension of the ion ITB regime may be possible, if the ion heating power is increased, which will be experimentally confirmed by the new installation of perpendicular NBI (BL5) in the near future.

Acknowledgement

This work was supported by the National Institute for Fusion Science (NIFS), (NIFS09-ULBB701).

[1] M. Yokoyama *et al.*, Phys. Plasmas **15**, 056111-1 (2008).
[2] O. Kaneko *et al.*, Plasma Fusion Res. **4**, 027 (2009).
[3] K. Ida *et al.*, Phys. Plasmas **16**, 056111 (2009).
[4] Y. Koide *et al.*, Phys. Rev. Lett. **72**, 3662 (1984).
[5] T. Fujita *et al.*, Nucl. Fusion **38**, 207 (1998).
[6] T. Fujita, Plasma Phys. Control. Fusion **44**, A19 (2002).
[7] R. C. Wolf, Plasma Phys. Control. Fusion **45**, R1 (2003).
[8] F. Ryter *et al.*, Phys. Rev. Lett. **86**, 5498 (2001).
[9] H. Yamada *et al.*, Nucl. Fusion **43**, 749 (2003).
[10] M. Yokoyama *et al.*, Contrib. Plasma Phys. **50**, 586 (2010).