High $T_e$, low collisional plasma confinement characteristics in LHD


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Abstract. High electron temperature ($T_e$) plasmas of more than 15 keV were achieved due to the upgraded electron cyclotron resonance heating system with newly installed 77 GHz-over 1 MW gyrotrons in the Large Helical Device. The value of $T_e$ greatly exceeds ~10 keV, which was obtained in previous experiments. The configuration dependence of high $T_e$ plasma performance was investigated under the magnetic field strength of ~2.7 T and the optimum configuration for achieving high $T_e$ plasma was observed. These high $T_e$ plasmas accompanied an electron internal transport barrier (e-ITB). Clear threshold of density-normalized ECRH power for an e-ITB formation was found. The foot point of an e-ITB moved outward during ECRH injection and the flat $T_e$ profile gradually healed with the propagation of the e-ITB foot point. The foot point finally reached to a lower order rational surface of $\nu/2\pi = 0.5$.

1. Introduction

An electron internal transport barrier (e-ITB) is characterized by a steep gradient formation in an electron temperature profile, a formation of a strong radial electric field (and/or its shear) and a decrease in an electric thermal diffusivity in a plasma core region [1, 2]. Up to now, this improved mode has been observed in several devices and has been intensively investigated [3-6]. There is a hypothesis based on some experimental results that lower-order rational surfaces or a local minimum of a safety factors play a important role for an e-ITB formation in both tokamaks and helical devices [1, 7-10]. One of the key issues for the e-ITB study is to clarify an effect of a rotational transform on an e-ITB formation.

Since 2006, the installation of 77 GHz gyrotrons with each output power of over 1 MW has progressed in the Large Helical Device (LHD) [11]. These high power gyrotrons enabled us to achieve a higher electron temperature ($T_e$) than that previously obtained [12] and also to survey properties of high $T_e$ plasmas in wide configuration range due to the oscillation frequency selected as 77 GHz, which is different from those of the gyrotrons already installed in the LHD. Such low collisional plasmas are suitable for an investigation of a configuration effect on plasma characteristics in toroidal systems. One of the important advantages of electron cyclotron resonance heating (ECRH) is that perpendicularly injected ECRH can produce plasmas without driven toroidal current. A mechanism of an e-ITB formation relating with lower order rational surfaces has been studied in LHD [10, 13]. Most of the previous e-ITB experiments were carried out using centre-focused ECRH overlapping to plasmas sustained by neutral beam injection (NBI). There were always effects of inductive return current against NBI driven current on the position of the rational surface because the relaxation time of the return current in LHD is several seconds, which is generally longer than the plasma sustainment time [14]. Thus it becomes possible to investigate the dynamics of e-
ITB formation and the relation between the foot point and the lower-order rational surfaces without the effect of return current by using high-power ECRH alone.

2. Experimental Setup

The LHD is the largest heliotron device with $R = 3.9$ m, $a = 0.6$ m, and has a pole number of 2 and a toroidal period of 10 [15]. The heliotron configurations are produced by a set of helical winding coils and three sets of poloidal field coils, which are all superconducting magnets. The magnetic field on the axis is $\sim 2.9$ T. In the LHD, an ECRH system with eight gyrotrons, whose frequencies are 77 (the new tube developed through the joint program with Tsukuba University, JAEA and Toshiba Electron Tubes & Devices; TETD), 82.7 (Gycom), 84 (Gycom) and 168 GHz (TETD), has been operated for preionization and plasma heating [16]. Of these, the high power 77-GHz gyrotrons with the output power of more than 1 MW have been operated since the 11th experimental campaign. Figure 1 (a) shows the history of ECRH port-through power. In the present state, three 77 GHz gyrotrons are operational for plasma experiments. The total injection power of ECRH to the plasma significantly increased due to the installation of the 77 GHz tubes and reached a value of 4 MW. The actual value of the simultaneous injection power to LHD is slight small ($\sim 3.7$ MW) because the total input power for the gyrotrons is limited by the power capacity of the transformer. The poloidal magnetic surfaces with the injected electron cyclotron (EC) wave beams are illustrated in Fig.1 (b) and (c) for the magnetic configuration of $R_{ax} = 3.75$ m, $B_t = 2.75$ T. The EC wave beams are injected to plasma from upper, lower and horizontal antennas. In the cases that the resonance surfaces do not exist around the plasma centre in the horizontally-elongated surface as 168-GHz beam shown in Fig. 1 (c), the horizontally-injected beams are focused on the plasma axis in the vertically-elongated surface by toroidally oblique injection.

However a Thomson scattering system is one of the most reliable diagnostics for $T_e$ measurement in toroidal devices, error bars of $T_e$ data sometimes become large for high-$T_e$, low-$n_e$ discharges due to the low intensity of the scattered light. In order to improve an accuracy of $T_e$ data, we carried out discharges with the fixed parameters such as $T_e$ and $n_e$ to accumulate the Thomson scattered light and three YAG lasers firing all together to increase the scattered light intensity [17]. Figure 2 shows the dependence of $T_e$ error on the accumulation number of the discharges. The $T_e$ error is normalized by the value for $n = 1$. The open squares indicate the case of only one YAG laser firing as the usage for regular experiments and the solid squares are those of three lasers firing. As can be seen from Fig. 2, $T_e$ error decreases with the dependence of $1/n^{-0.5}$. Three lasers firing was more effective and

FIG. 1. (a) the history of ECRH port-through power, the injected EC wave beams in (b) the vertically and (c) the horizontally elongated magnetic surface for the magnetic configuration of $R_{ax} = 3.75$ m, $B_t = 2.75$ T.
highly accurate $T_e$ could be successfully obtained by lesser discharge accumulation compared with the single laser firing. For steady state plasmas, $T_e$ error can be decreased by time frame accumulation too. These technical methods for the improvement of $T_e$ measurement accuracy is summarized in Ref [17].

3. Configuration dependence

In the LHD, the configuration dependence of the confinement property has been studied and it has been pointed out the inward-shifted configuration $R_{ax} = 3.53$ m is optimum from the view point of neoclassical transport [18]. This was experimentally examined in the previous experiments for the low collisional plasmas ($T_e \sim 1.5$ keV, $0.3 \leq n_e \leq 1.5 \times 10^{19}$ m$^{-3}$) produced by ECRH alone [19]. In the present research, much lower collisional plasmas were treated and it was expected that the neoclassical characteristics for the plasma confinement emerges more clearly. We started from the configuration optimization for the production of high $T_e$ plasmas.

Figure 3 shows (a) the radial profiles of $T_e$ for three configuration cases; $(R_{ax}, B_0) = (3.53$ m, $2.705$ T), $(3.60$ m, $2.705$ T) and $(3.75$ m, $2.75$ T) with approximately same electron density of $n_e \sim 0.4 \times 10^{19}$ m$^{-3}$ and same injection power of $P_{ECRH} \sim 2.7$ MW, the dependence of (b) the central electron temperature $T_{e0}$ and (c) $R_{ax}/L_{Te}$ on $R_{ax}$, where $R_{ax}$ is magnetic axis position, $B_0$ is the magnetic field on axis, $L_{Te}$ is the radial scale length of $T_e$ and $R_{ax}/L_{Te}$ represents a performance of an e-ITB. The data in Fig.3 (b) and (c), $n_e$ was approximately same value of $\sim 0.5 \times 10^{19}$ m$^{-3}$ but $P_{ECRH}$ was different. $L_{Te}$ were evaluated at $r_{eff}/a_99 = 0.2$, where $r_{eff}$ is the effective minor radius and $a_99$ is the averaged minor radius where the 99 % of the stored energy is confined. The plasmas were produced and sustained only by centre-focused ECRH. As can be seen from Fig. 3, the steepest profile and the highest $T_{e0}$ were obtained for $R_{ax} = 3.53$ m. $R_{ax}/L_{Te}$ for $R_{ax} = 3.53$ m was 1.5 times larger than that for the other configurations.

FIG. 3. (a) the radial profiles of $T_e$ for three configuration cases; $(R_{ax}, B_0) = (3.53$ m, $2.705$ T), $(3.60$ m, $2.705$ T) and $(3.75$ m, $2.75$ T), the configuration dependence of (b) the central electron temperature $T_{e0}$ and (c) $R_{ax}/L_{Te}$.
PHA, SXCCD and ECE measurement showed that there was a certain amount of superthermal electrons in these high $T_e$, low collisional plasmas [20]. However, we have already confirmed that there was only small effect of the superthermal electrons for the bulk plasma temperature evaluation by the Thomson scattering measurement [17]. We confirmed that the superthermal electrons tend to be produced when an ECRH was obliquely injected to plasma. An increase of superthermal electrons may decrease the deposition power to bulk plasma because a part of the ECRH power is used for the production and/or the acceleration of the superthermal electrons.

We experimentally evaluated the electron thermal diffusivity $\chi_e$ and compared with the neoclassical one calculated using GSRAKE code, which solves the ripple-averaged drift kinetic equation [21, 22]. Figure 4 shows the radial profiles of $\chi_e$ for the three cases in Fig. 3 (a). The solid and open symbols represent the experimental and calculated $\chi_e$, respectively. The experimental $\chi_e$ was simply obtained as $-P_{ECRH}/(S_{ne}\partial T_e/\partial r_{eff})$ under the assumption that the energy transfer to the ion was negligible and the plasma was in steady state, where $S$ is the area of the toroidal surface. The tendency of the experimental $\chi_e$ behaviour qualitatively agree with that of the calculation and the lowest $\chi_e$ values were obtained for the configuration of $R_{ax} = 3.53$ m in both experiments and calculation. Thus $R_{ax} = 3.53$ m is thought to be better configuration for an achievement of higher $T_e$ plasmas in the LHD. This result is consistent with previous studies reported in Ref [18, 19].

4. Characteristic of e-ITB formation

Here we investigated a criterion of an e-ITB transition and the formation process of the e-ITB structure for a high $T_e$, low collisional plasma. Figure 5 shows the radial profiles of (a) $T_e$ for four $n_e$ cases; 0.23, 0.50, 0.73, 0.77×10$^{19}$ m$^{-3}$ and (b) the radial electric field $E_r$ calculated using the GSRAKE code.
using the GSRAKE code. The rotational transform ($\nu/2\pi$) profile for a vacuum condition is also attached in Fig. 5 (a). Clear $n_e$ threshold (and/or $P_{\text{ECRH}}/n_e$ threshold) for the formation of the e-ITB was observed. The $T_e$ profile drastically changed from flat to peaked one in the narrow range of $0.73 \leq n_e \leq 0.77\times10^{19} \text{ m}^{-3}$. Both the shoulder point of the flat $T_e$ profile and the foot point of the e-ITB located at $r_{\text{eff}} \sim 0.27 \text{ m}$ and were coincident with the rational surface of $\nu/2\pi = 0.5$. In Figure 5 (b) it is found that the positive $E_r$ formation at the core region in the peaked $T_e$ profiles and the core electron root confinement, which is improved confinement regime specific in helical plasmas [23] was achieved. On the other hand, $E_r$ for the case of $n_e \sim 0.77\times10^{19} \text{ m}^{-3}$ was negative and the absolute value was considerably smaller than those of the other three. We also experimentally observed the positive $E_r$ formation by the heavy ion beam probe measurement [24] for the peaked $T_e$ discharges. Figure 6 shows the dependence of $T_{e0}$ on density-normalized ECRH power ($P_{\text{ECRH}}/n_e$) for $R_{\text{ax}} = 3.53 \text{ m}, B_0 = 2.705 \text{ T}$. All these plasmas were produced and sustained by ECRH alone. Clear threshold of $P_{\text{ECRH}}/n_e$ for the formation of the e-ITB was found. Once the e-ITB formed, $T_{e0}$ increased with the proportional dependence of $-(P_{\text{ECRH}}/n_e)^{0.5}$. Finally more than 15 keV of $T_{e0}$ was successfully achieved for low $n_e$ plasmas ($n_e \leq 0.23\times10^{19} \text{ m}^{-3}$).

FIG. 7. The time evolution of (a)-(d) $T_e$, $n_e$ profile, (e) $T_e$ gradient at $r_{\text{eff}} = 0.078 \text{ m}$ and (f) $T_e$ slightly inside the rational surface of $\nu/2\pi = 0.5$. 

FIG. 6. the dependence of $T_{e0}$ on density-normalized ECRH power for $R_{\text{ax}} = 3.53 \text{ m}, B_0 = 2.705 \text{ T}$. 

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FIG. 5. (a) $\nu/2\pi$ profile for a vacuum condition is also attached. Clear $n_e$ threshold (and/or $P_{\text{ECRH}}/n_e$ threshold) for the formation of the e-ITB was observed. The $T_e$ profile drastically changed from flat to peaked one in the narrow range of $0.73 \leq n_e \leq 0.77\times10^{19} \text{ m}^{-3}$. Both the shoulder point of the flat $T_e$ profile and the foot point of the e-ITB located at $r_{\text{eff}} \sim 0.27 \text{ m}$ and were coincident with the rational surface of $\nu/2\pi = 0.5$. In Figure 5 (b) it is found that the positive $E_r$ formation at the core region in the peaked $T_e$ profiles and the core electron root confinement, which is improved confinement regime specific in helical plasmas [23] was achieved. On the other hand, $E_r$ for the case of $n_e \sim 0.77\times10^{19} \text{ m}^{-3}$ was negative and the absolute value was considerably smaller than those of the other three. We also experimentally observed the positive $E_r$ formation by the heavy ion beam probe measurement [24] for the peaked $T_e$ discharges. Figure 6 shows the dependence of $T_{e0}$ on density-normalized ECRH power ($P_{\text{ECRH}}/n_e$) for $R_{\text{ax}} = 3.53 \text{ m}, B_0 = 2.705 \text{ T}$. All these plasmas were produced and sustained by ECRH alone. Clear threshold of $P_{\text{ECRH}}/n_e$ for the formation of the e-ITB was found. Once the e-ITB formed, $T_{e0}$ increased with the proportional dependence of $-(P_{\text{ECRH}}/n_e)^{0.5}$. Finally more than 15 keV of $T_{e0}$ was successfully achieved for low $n_e$ plasmas ($n_e \leq 0.23\times10^{19} \text{ m}^{-3}$).
Figure 7 shows the time evolution of (a)-(d) $T_e$ and $n_e$ profile, (e) $T_e$ gradient at $r_{\text{eff}} = 0.078$ m and (f) $T_e$ slightly inside the rational surface of $\nu/2\pi = 0.5$ under $R_{\text{ax}} = 3.53$ m, $B_0 = 2.705$ T. The rotational transform profile for a vacuum condition is attached in (a)-(d) and the rational surface of $\nu/2\pi = 0.5$ is located at $r_{\text{eff}} \sim 0.25$ m. ECRH was injected perpendicularly during $t = 0.21 - 0.71$ s with $P_{\text{ECRH}} = 2.63$ MW. Highly accurate $T_e$ profiles were successfully obtained by the accumulation of the intensity of Thomson scattered light through 20 discharges with the three YAG lasers all injected together. At the beginning of the discharge, a flat $T_e$ profile with a small bump was observed and a peaked $T_e$ profile was formed at $t = 0.5$ s. After that the foot point of the e-ITB moved outward with increasing $T_{\text{e0}}$. As can be seen from Fig. 7 (a)-(d), steep gradient of $T_e$ formed in the vicinity of the rational surface, which was larger than that in the e-ITB region. Fig. 7 (e) indicates that $T_e$ at the core region increased with the foot point moving outward and the e-ITB growing such that the $T_e$ gradient increased during the discharge. On the other hand, $T_e$ just inside the rational surface (at $r_{\text{eff}} = 0.21$ and 0.24 m) gradually decreased as shown in Fig. 7 (f) leading to the increase of the $T_e$ gradient at the core region and to the decrease of that around the rational surface. Finally, the $T_e$ gradient at the e-ITB region equated with that around the rational surface indicating that (i) the foot point of the e-ITB reached to the position of the rational surface of $\nu/2\pi = 0.5$ and (ii) the e-ITB plasma with only one folding point in its $T_e$ profile was formed. We also observed same $T_e$ profile behavior in higher density plasmas up to $n_e = 0.73 \times 10^{19}$ m$^{-3}$.

5. Summary

We investigated the confinement characteristics of the high $T_e$, low collisional plasmas produced by high power ECRH in LHD. Highly accurate high-$T_e$ profiles were successfully obtained by the accumulation of the intensity of Thomson scattered light by fixed shot accumulation and the simultaneous firing with three YAG lasers. The configuration survey was carried out and the highest $T_e$ and the steepest profile were obtained for the configuration of $R_{\text{ax}} = 3.53$ m, which is predicted as the optimum condition in the view point of neoclassical transport. Clear $n_e$ threshold (and/or $P_{\text{ECRH}}/n_e$ threshold) for the formation of the e-ITB was observed. The $T_e$ profile drastically changed from flat to peaked one in the narrow $n_e$ range and the $E_r$ made a transition from negative to positive at the core region. Once the e-ITB formed, $T_{\text{e0}}$ increased with the proportional dependence of $\sim (P_{\text{ECRH}}/n_e)^{0.5}$ and finally more than 15 keV of $T_{\text{e0}}$ was successfully achieved. We investigated the formation process of the e-ITB structure for a high $T_e$, low collisional plasma. The foot point of an e-ITB moved outward during the ECRH injection and the flat $T_e$ profile gradually healed with the propagation of the e-ITB foot point. We found that the increase of $T_e$ at the core region was due to the foot point moving outward and the e-ITB growing. The foot point finally reached to a lower order rational surface of $\nu/2\pi = 0.5$ and the e-ITB plasma with only one folding point in its $T_e$ profile was formed.

References


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