Improvement of Ion Confinement in Core Electron-Root Confinement (CERC) Plasmas in Large Helical Device

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An increase in ion temperature has been observed with superposition of centrally focused electron cyclotron resonance heating (ECRH) to plasmas heated by high-energy neutral beam injection (NBI) in Large Helical Device. The ion-temperature (T_i) rise is accompanied by the formation of electron internal transport barrier (ITB). A transport analysis shows that ion transport as well as electron transport is improved with the reduction of anomalous transport. A neoclassical ambipolar flux calculation shows a positive radial-electric field (E_r) in the region of the T_i rise, and E_r should suppress the enhancement of ripple transport due to the T_i-rise. These analyses indicate the ion transport improvement in the core electron-root confinement plasmas. Toroidal rotation is driven in the co-direction by applying ECRH, and the toroidal rotation velocity is increased with the T_i rise. A correlation between the T_i rise and toroidal rotation is suggested.

Keywords: core electron-root confinement, neoclassical transport, anomalous transport, radial electric field, ion transport, toroidal rotation, electron internal transport barrier

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1. Introduction

Helical devices have non-axisymmetric magnetic field configuration, which induces neoclassical ripple transport. Neoclassical ion and electron fluxes are strongly dependent on the radial electric field (E_r), whose value is determined by the ambipolarity condition of these fluxes. E_r also has a great influence on the plasma properties related to both ripple and anomalous transport. In major middle-sized helical devices such as CHS, W7-AS, and TJ-II, the improvement of electron transport is commonly observed in core electron-root confinement (CERC) plasmas [1, 2], in which a large positive E_r is observed in the core region. The CERC plasmas are obtained when the central electrons are strongly heated with electron cyclotron resonance heating (ECRH), and they are also observed in Large Helical Device (LHD) [3–5]. In the CERC plasmas, an electron internal transport barrier (electron-ITB) with a steep gradient of the electron-temperature (T_e) profile is formed in the core region, and the core electron transport is improved in the neoclassical electron root with the positive E_r [1, 2, 6]. As a result, high T_e is achieved in the CERC plasmas.

The confinement improvement in the neoclassical electron root is specific to helical systems, and ion transport should also be improved in the CERC plasmas according to a theoretical prediction. We have observed an ion-temperature (T_i) rise in the neutral beam injection (NBI) plasma by applying centrally focused ECRH in LHD, in which the T_e profile shows electron-ITB formation. It is thought that the T_i rise is ascribed to the ion transport improvement in the CERC plasmas. A transport analysis and a comparison with the neoclassical calculation are carried out, and the results are discussed. The properties of the CERC plasmas, which are realized by applying ECRH to the NBI plasmas, are presented with a view of ion transport improvement.

2. NBI and ECRH Systems

LHD is the world's largest superconducting helical device [7], and it is equipped with NBI and ECRH systems for plasma heating. The NBI system consists of three high-energy negative-ion-based NB injectors [8, 9] and a low-energy positive-ion-based NB injector [10]. The arrangement of the NBI system is illustrated in Fig. 1. The injection direction of the negative-NBI is tangential while that of the positive-NBI is perpendicular to the magnetic axis. The injection energy of the negative-NBI is as high as 180 keV and plasma electrons are dominantly heated. The total injection power achieved is 14 MW in the negative-NBI. To increase the ion heating power effectively with the negative-NBI, high-Z discharges are utilized in high-T_i experiments with Ar/Ne gas puffing [11]. As a result, T_i is increased with an increase in ion heating power and

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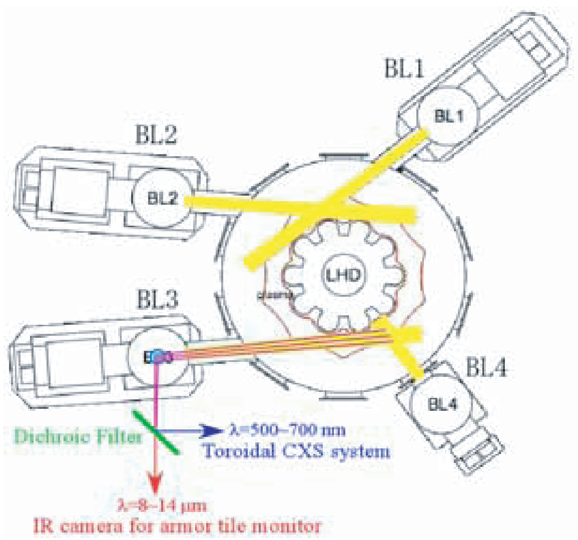

Fig. 1 Arrangement of three high-energy tangential NB injectors (BL1, BL2, and BL3) and a low-energy perpendicular NB injector (BL4). A toroidal line of sight from the BL3-injection port for the CXS system, which utilizes the BL4 beam, is also indicated.

reached 13.5 keV [12]. For efficient ion heating in hydrogen plasmas, the positive-NBI has been recently constructed with an injection energy of 40 keV, which dominantly heats plasma ions, and 6 MW of injection power was achieved [10]. The positive-NBI is also utilized for a T_i-profile measurement by charge-exchange spectroscopy (CXS) along a toroidal line of sight [13, 14], which is better for the measurement in the central region than that along a poloidal line of sight. With this arrangement, toroidal rotation is also measured.

The ECRH system employs 168, 84, and 82.7 GHz gyrotrons [15]. Each microwave is injected as a highly focused Gaussian beam using vertical and horizontal antenna systems with quasi-optical mirrors. The beam-waist radius at the focal point is 15-30 mm. The focus location is variable at 3.5-3.9 m of the major radius on the equatorial plane. The total injection power achieved is 2.1 MW. In the experiments, the second-harmonic heating with 84 and 82.7 GHz microwaves is used at around 1.5 T of the magnetic field strength on the axis.

3. Ion Temperature Rise in the CERC Plasmas

CERC is a specific feature commonly observed in helical systems, and no counterpart is observed in tokamaks. In LHD, by applying centrally focused ECRH to the NBI plasma, a strongly peaked T_e profile is observed in the core region. Such a kind of the electron-ITB formation indicates improvement of electron transport, and reduction of electron thermal diffusivities is recognized together with positive radial electric field (E_r). This means that the improvement of electron transport in the core region occurs in the neoclassical electron root. Ion transport is also expected to be improved in the electron root, and ECRH was applied to plasmas heated by both the negative-NBI and the positive-NBI.

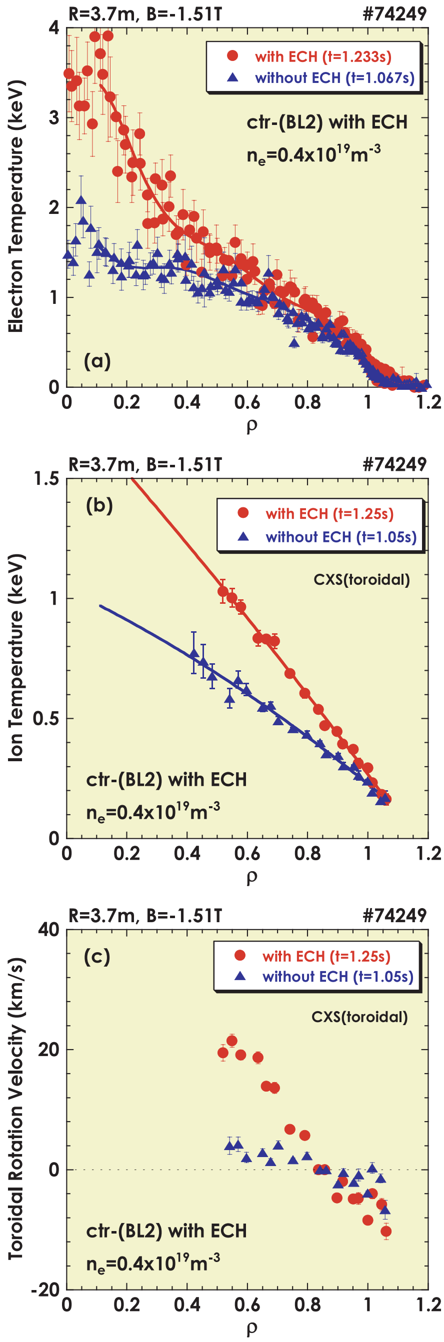

Fig. 2 (a) Electron temperature profiles, (b) ion temperature profiles, and (c) toroidal rotation velocity profiles, with and without ECRH superposition to the plasmas heated with both the counter-NBI (BL2) and the perpendicular-NBI (BL4). While the electron temperature profiles are polynomially fitted, the ion temperature profiles are parabolically extrapolated to the center.

Figure 2 (a) and (b) shows the electron and ion temperature profiles, respectively, in the plasmas with and without the ECRH superposition. The electron density is

0.4×10^{19} m^{-3}, and the target plasma is sustained by the counter-NBI (BL2) and the perpendicular-NBI (BL4). The applied ECRH power is 0.68 MW and is focused at about $\rho = 0.15$. By applying ECRH, the T_e profile indicates a steep gradient inside $\rho = 0.4$, which shows improvement of electron confinement in the electron root. T_i is also increased along with the T_e rise, as shown in Fig. 2 (b). The ion temperature is measured using the charge exchange emission of CVI, and the carbon impurity profile in the core region is strongly hollowed due to the impurity pump-out effect when ECRH is applied. As a result, the central T_i profile is not measured. Although it is unknown how much the central T_i is increased by the ECRH superposition, a T_i rise is observed in the mid-radius region. It seems that the T_i-rise location is different from the T_e-rise location.

Toroidal rotation is also measured by CXS in a tangential line of sight. Figure 2 (c) shows the toroidal rotation velocity, V_t, for the plasmas with and without applying ECRH. It is found that the toroidal rotation is driven in the co-direction at the T_i-rise location by applying ECRH. The increase in the toroidal rotation seems to be correlated with the T_i rise, and the spontaneous toroidal rotation due to applying ECRH is suggested to cause the transport improvement.

A transport analysis based on power balance was performed for the plasmas with and without applying ECRH shown in Fig. 2. Since T_i data in the central region is not available, the T_i profiles are parabolically extrapolated to the center using the measured data, as shown in Fig. 2 (b). Thus, ion transport in the central region is not discussed here. As for electron transport, since the heat exchange between electrons and ions is almost negligible in such low-density plasmas, the electron thermal diffusivity is obtained in the entire region. Z_{eff} is usually 2 to 3 in hydrogen plasmas, and the Z_{eff} profile should be changed due to the impurity pump-out effect in the central region with the ECRH superposition. The Z_{eff} profile change would influence the injected neutral-beam deposition (ionization) profile. In LHD, the beam deposition power is estimated using a shine-through power measurement on the beam-facing armor plate [16], and no distinct change of the beam deposition power was observed with the ECRH superposition. This is probably because Z_{eff} in the NBI plasmas without the ECRH superposition is not high, and the influence of the Z_{eff} change due to the ECRH superposition on the beam deposition is considered to be small. Therefore, the effect of the Z_{eff} change is not taken into consideration to estimate the beam deposition profile.

Figures 3 (a) and (b) show the thermal diffusivities for electrons and ions normalized by the gyro-Bohm factor of $T_e^{3/2}$ and $T_i^{3/2}$, respectively. $\chi_e/T_e^{3/2}$ and $\chi_i/T_i^{3/2}$ are regarded as measures of the degree of anomalous transport for electrons and ions, respectively. As shown in Fig. 3, by applying ECRH, the thermal diffusivity normalized by the gyro-Bohm factor for ions is reduced in the region of $\rho > 0.5$ while that for electrons is not changed in the same region. In the central region of $\rho < 0.5$, $\chi_e/T_e^{3/2}$ is reduced by applying ECRH, although the change in ion transport in the central region is unknown. These results suggest that the location of the transport improvement by applying ECRH is different between electrons and ions.

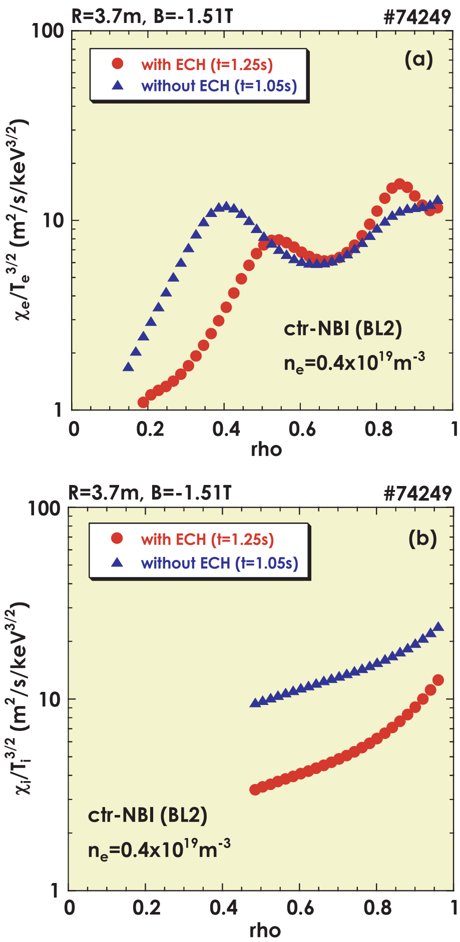

Fig. 3 Profiles of (a) electron thermal diffusivities normalized by $T_e^{3/2}$, $\chi_e/T_e^{3/2}$, and (b) ion thermal diffusivities normalized by $T_i^{3/2}$, $\chi_i/T_i^{3/2}$, for the NBI plasmas with and without the ECRH superposition shown in Fig. 2.

The neoclassical calculation was also performed for the plasmas shown in Fig. 2. The GSRAKE code was used [17], and the calculated ambipolar E_r is shown in Fig. 4 (a). Positive E_r is found at around $\rho = 0.6$, which corresponds to the T_i-rise location. The value of the positive E_r is not large, and the obtained electron root is a single solution. The calculated ion thermal diffusivities, χ_i, including the E_r effect, are shown in Fig. 4 (b), and it is found that the neoclassical χ_i is not increased with the T_i rise. Ripple transport is greatly enhanced without E_r, and the positive-E_r effect suppresses the enhancement of ripple transport due to the T_i rise. Considering that the neoclassical χ_i is not changed much by applying ECRH, the T_i-rise is thought to be caused by the reduction of anomalous transport.

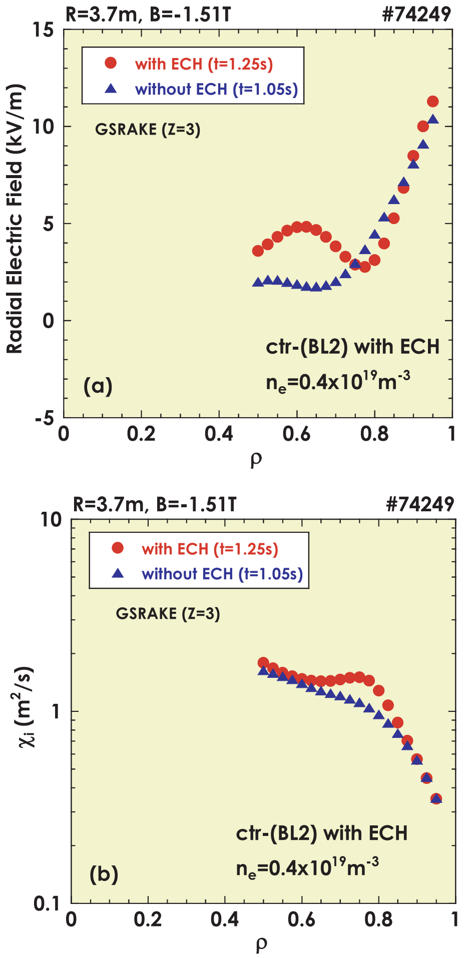

Fig. 4 Results of the neoclassical calculation using the GSRAKE code for the plasmas with and without the ECRH superposition shown in Fig. 2 (a). Radial electric-field profiles and (b) ion thermal-diffusivity profiles.

4. Discussion

In previous investigations on the electron-ITB in LHD, which have been reported in Refs. [3–6], no increase in T_i was observed in the CERC plasmas. In those experiments, only high-energy negative-NBI heating was used in the target plasmas for the ECRH superposition, and the ion heating power ratio was much smaller than the electron heating one. In the present experiments, on the other hand, low-energy positive-NBI heating is used together with the negative-NBI in the target plasmas, and the ion heating power ratio is enhanced compared with the previous experiments. As a result, the change in T_i would be more sensitive to the change in ion transport, and thus, a T_i rise has been observed in the present experiments. In the previous experiments, the T_i measurement was performed by CXS in a poloidal line of sight with a high-energy beam with a small cross section for the measurement. In that case, the peripheral T_i would have an influence on the core T_i measurement under such an experimental condition, as the ECRH superposition causes the impurity pump-out effect. In the present experiments, CXS in a toroidal line of sight is employed with a low-energy beam with a larger cross section for the measurement. Thus, the T_i-profile measurement should be improved for observation of the T_i-change. Another hypothesis considers the density profile. There is a tendency that the density-profile hollowness is suppressed with low-energy NBI heating [13]. Although the increase in the T_e/T_i ratio in the CERC plasmas could destabilize the ion temperature gradient (ITG) mode, the destabilization of the ITG mode could be suppressed due to this effect with low-energy NBI heating.

The T_e/T_i ratio is one of the important parameters for ion transport. In tokamaks, it has been reported that increasing the T_i/T_e ratio decreases electron and ion transport [18]. This is related to the ITG mode, and it is thought that an increase in the T_e/T_i ratio leads to lowering the critical ion temperature gradient for the destabilization of the ITG mode. Considering that the electron confinement is improved in the LHD-CERC plasmas, in which the T_e/T_i ratio increases, the same discussion as that for tokamaks would not be necessarily applied. However, an excess increase in the T_e/T_i ratio would lead to the destabilization of the ITG mode, which would suppress the T_i increase. On the other hand, the density gradient would also be related to the ITG mode, and low-energy NBI heating, in which the density hollowness is suppressed, may play a role in stabilization of the ITG mode. In LHD, the T_i profile measurement by CXS is improved with the combination of the injected low-energy neutral beams and the toroidal line of sight for the measurement. The correlation between the T_e/T_i ratio and ion transport in the CERC plasma is an important subject to be solved, and its investigation has just started with the results presented in this article with the improved CXS measurement.

E_r plays an important role in the confinement improvement, and it would also influence the direct loss of energetic ions, especially for the perpendicularly injected particles. It is predicted that the loss of energetic ions with a specific pitch angle is reduced with positive E_r. In LHD, the behavior of energetic ions in the CERC plasmas is investigated with neutral particle analyzers; however, the reduction of the direct ion loss with ECRH superposition has not been observed definitely. Thus, although this E_r effect for energetic ions should be investigated further, enhancement of the NBI heating power due to the reduction of the direct ion loss is not considered with ECRH superposition in the present analyses.

As shown in Fig. 2 (c), toroidal rotation driven by ECRH superposition seems to be correlated with the T_i rise. The neoclassical calculation code for the toroidal viscosity is being developed for the LHD high-T_i plasmas; however, the neoclassical prediction for toroidal rotation is not available currently. In near future, the correlation between toroidal rotation and ion transport would be clarified theoretically, including the effect of E_r on the toroidal viscosity. Then, the analysis of the experimental observation would be more understandable.

5. Summary

An increase in ion temperature has been observed in the NBI-heated plasmas with the superposition of centrally focused ECRH in LHD. The target plasma is produced with a high-energy NBI, and a low-energy NBI is also used for ion heating and a T_{i}-profile measurement by CXS. By applying ECRH to the NBI plasma, an increase in T_{e} is observed with a steep T_{e}-gradient. This indicates the formation of the electron-ITB, in which the improvement of electron transport is recognized in CERC. Therefore, it is thought that the T_{i} increase is observed in CERC conditions. The location of the T_{i} rise seems to be different from that of the T_{e} rise. The transport analysis shows that the ion transport improvement is ascribed to the reduction of anomalous transport. Neoclassical ambipolar calculation shows that E_{r} is positive at the location of the T_{i}-rise. This suggests that ion transport is improved in the CERC plasma. Considering that the neoclassical ion thermal diffusivity is not changed much, the experimental ion transport is dominated by anomalous transport. Toroidal rotation is measured by CXS in a toroidal line of sight, and a correlation is observed between toroidal rotation and the T_{i}-rise by applying ECRH.

The improvement of ion transport in CERC is a possible scenario for increasing the ion temperature in helical systems, and this is experimentally demonstrated in LHD.

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