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

Y. Takeiri, M. Yokoyama, K. Nagaoka, K. Ida, S. Kubo, T. Shimozuma, H. Funaba, M. Osakabe, K. Ikeda, K. Tsumori, Y. Oka, M. Yoshinuma, S. Morita, M. Goto, K. Narihara, I. Yamada, K. Tanaka, O. Kaneko, A. Komori, and LHD Experimental Group

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

(Received 2 November / Accepted 2 November)

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

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

1. Introduction

The helical devices have non-axisymmetric magnetic field configuration, which induces neoclassical ripple transport. The neoclassical ion and electron fluxes are strongly dependent on the radial electric field (E_r), the value of which is determined by the ambipolarity condition of these fluxes. The E_r also has a great influence on the plasma properties related to both the ripple transport and the anomalous transport. In major middle-sized helical devices such as CHS, W7-AS, and TJ-II, the improvement of the electron transport is commonly observed in the core electron-root confinement (CERC) plasmas [1,2], in which large positive E_r is observed in the core region. The CERC plasmas are obtained when the central electrons are strongly heated with the ECRH (electron cyclotron resonance heating), and they are also observed in Large Helical Device (LHD) [3-5]. In the CERC plasmas, the electron internal transport barrier (electron-ITB) with a steep gradient on the 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 the helical system, and the ion transport should also be improved in the CERC plasmas in the theoretical prediction. We have observed a T_i rise in the NBI (neutral beam injection) plasma by applying the centrally focused ECRH in LHD, in which the T_e profile shows the electron-ITB formation. It is thought that the T_i rise is ascribed to the ion transport improvement in the CERC plasma. The transport analysis and the comparison with the neoclassical calculation are carried out, and the results are discussed. In the following, the plasma properties of the CERC plasmas, which are realized by applying the ECRH to the NBI plasmas, are presented with a view of the ion confinement improvement.

2. NBI and ECRH Systems

The Large Helical Device (LHD) is the world's largest superconducting helical device [7], and it is equipped with NBI and ECRH systems for the 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 systems 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 180keV and the plasma electrons are dominantly heated. The total injection power achieved is 14MW in the negative-NBI. To

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

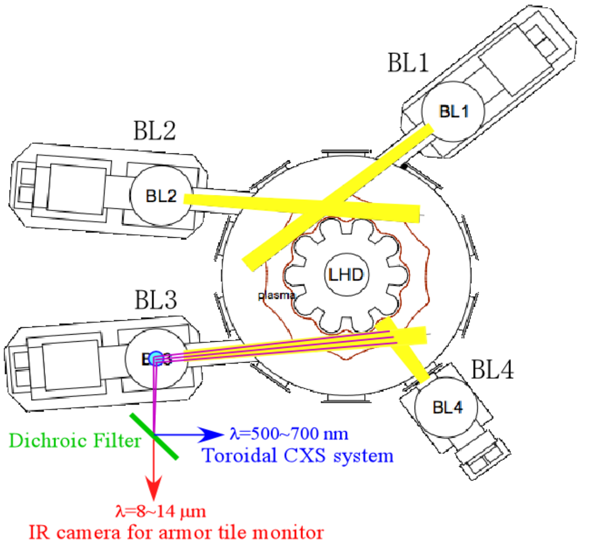

Fig.1 Arrangement of three high-energy tangential NB injectors (BL1, BL2 and BL3) and a low-energy perpendicular NB injector (BL4). A toroidal line of sight from the BL3 injection port for the CXS system, which utilizes the BL4 beam, is also indicated.

increase the ion heating power effectively with the negative-NBI, high-Z discharges are utilized for the high-T_i experiments with Ar/Ne gas puffing [11]. As a result, the T_i is increased with an increase in the ion heating power, and reached 13.5keV [12]. For efficient ion heating in the hydrogen plasmas, the positive-NBI has been recently constructed with the injection energy of 40keV, which dominantly heats the plasma ions, and 6MW of the injection power was achieved [10]. The positive-NBI is also utilized for the T_i-profile measurement with the CXS (charge-exchange spectroscopy) 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, the toroidal rotation is also measured.

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

3. Ion Temperature Rise in the CERC plasmas

The core electron-root confinement (CERC) is a specific feature commonly observed in helical systems, and

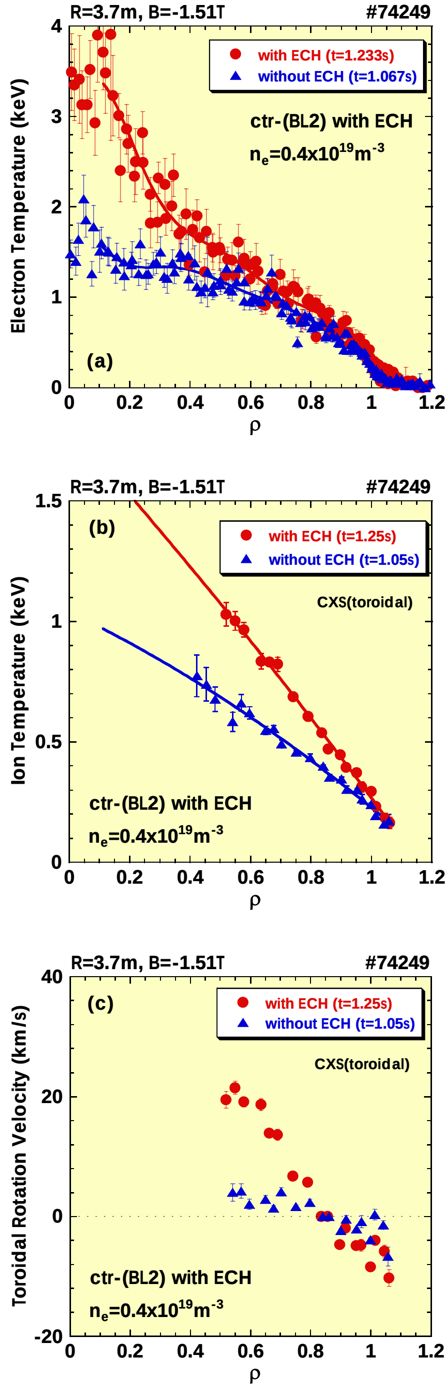

Fig.2 (a) Electron temperature profiles, (b) ion temperature profiles, and (c) toroidal rotation velocity profiles, for plasmas heated with the counter-NBI (BL2) and the perpendicular-NBI (BL4) with and without the ECRH superposition.

no counterpart in tokamaks. In LHD, by adding the 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 (internal transport barrier) formation indicates the improvement of the electron confinement, and the reduction of the electron thermal diffusivities is recognized together with positive radial electric field (E_r). This means that the improvement of the electron transport in the core region occurs in the neoclassical electron root. The ion transport is also expected to be improved in the electron root, and the ECRH was applied to the plasma heated by the negative-NBI and the positive-NBI.

Figures 2(a) and (b) show the electron and ion temperature profiles with and without the ECRH superposition, respectively. The electron density is $0.4\times10^{19}m^{-3}$ and the target plasma is sustained by the counter-NBI (BL2) and the perpendicular-NBI (BL4). The applied ECH power is 0.68MW and is focused at around ρ=0.15. By adding the ECRH the T_e profile indicates a steep gradient inside ρ=0.4, which shows the improvement of the electron confinement in the electron root. The T_i is also increased in association with the T_e rise, as shown in Fig. 2(b). The ion temperature is measured with 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 the 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, the 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.

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

The transport analysis based on the power balance was carried out for the plasmas with and without the ECRH applying shown in Fig. 2. Since there is no T_i data in the central region, the T_i profiles are parabolically fitted using the measured data, as shown in Fig. 2(b). Thus, the ion transport in the central region is not discussed here. As for the electron transport, since the heat exchange between the electrons and the ions is almost neglected in such a low-density plasma, the electron thermal diffusivity is obtained in the whole region. Figures 3(a) and (b) show the thermal diffusivities for the electrons and ions normalized by the gyro-Bohm factor of $T_e^{3/2}$ and $T_i^{3/2}$, respectively. The $\chi_e/T_e^{3/2}$ and the $\chi_i/T_i^{3/2}$ are regarded as a measure of the degree of the anomalous transport. As shown in Fig. 3, by adding the ECRH the thermal diffusivity normalized by the gyro-Bohm factor for the ions is reduced in the region of ρ>0.5 while that for the electrons is not changed in the

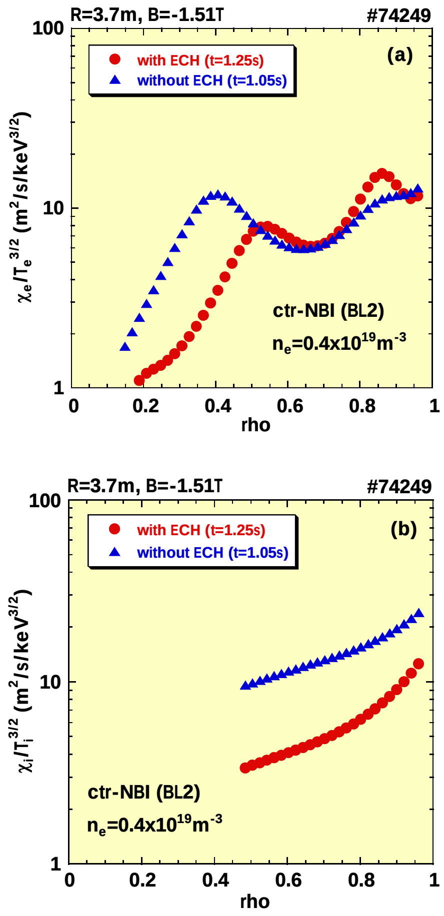

Fig.3 Profiles of (a) the electron thermal diffusivities normalized by $T_e^{3/2}$, $\chi_e/T_e^{3/2}$, and (b) the ion thermal diffusivities normalized by $T_i^{3/2}$, $\chi_i/T_i^{3/2}$, for NBI plasmas with and without the ECRH superposition shown in Fig. 2.

same region. In the central region of ρ<0.5, the $\chi_e/T_e^{3/2}$ is reduced by adding the ECRH although the change of the ion transport in the central region is unknown. These results suggest that the location of the transport improvement by adding the ECRH is different between the electrons and ions.

The neoclassical calculation was also carried out for the plasmas shown in Fig. 2. The used code is the GSRAKE code, and the calculated ambipolar E_r is shown in Fig. 4(a). Positive E_r is found at around ρ=0.6, which corresponds to the T_i-rise location. The value of the positive E_r is not so 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. The ripple transport is greatly enhanced without the E_r, and the positive-E_r effect suppresses the enhancement of

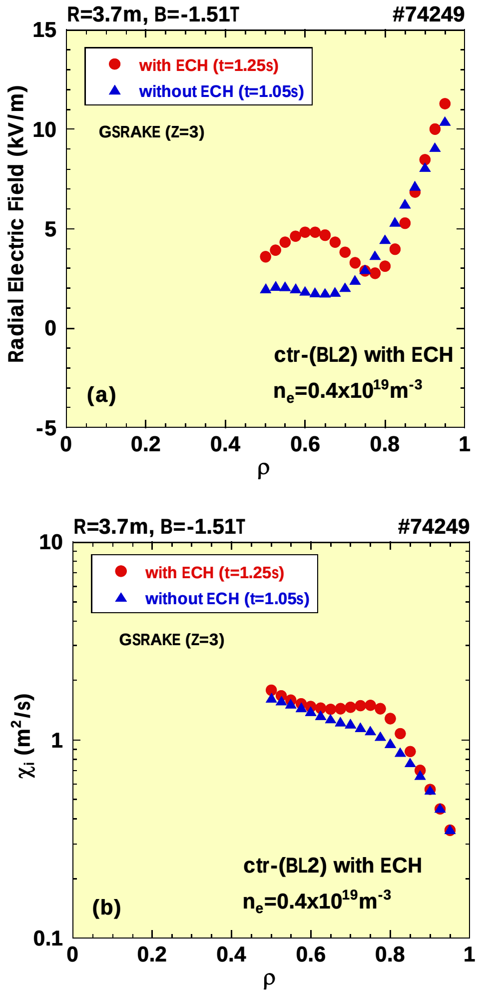

Fig.4 Results of the neoclassical calculation using the GSRAKE code for plasmas with and without the ECRH superposition shown in Fig. 2. (a) Radial electric-field profiles, and (b) ion thermal-diffusivity profiles.

the ripple transport due to the T_i rise. Considering that the neoclassical χ_i is not so changed by the ECRH applying, the T_i-rise is thought to be ascribed to the reduction of the anomalous transport.

4. Summary

An increase in the ion temperature has been observed in the NBI-heated plasmas with the superposition of the centrally focused ECRH in LHD. The target plasma is produced with high-energy NBI, and low-energy NBI is also utilized for the ion heating and the T_i-profile measurement with CXS. By adding the ECRH to the NBI plasma, an increase in T_e is observed with a steep T_e-gradient. That indicates the formation of the electron-ITB, in which the improvement of the electron transport is recognized in the CERC (core electron-root confinement). Therefore, it is thought that the T_i-increase is observed in the 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 the anomalous transport. The neoclassical ambipolar calculation shows that the E_r is positive at the location of the T_i-rise. This suggests that the ion confinement is improved in the CERC plasma. Considering that the neoclassical ion thermal diffusivity is not so changed, the experimental ion transport is dominated by the anomalous transport. The toroidal rotation is measured with the CXS in a toroidal line of sight, and a correlation is recognized between the toroidal rotation and the T_i-rise by adding the ECRH.

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

Acknowledgements

The authors are grateful to the technical staff in the LHD for the excellent operation of the LHD and the NBI and ECRH systems. This work has been supported by the NIFS under NIFS07ULBB501.

References

[1] M. Yokoyama, *et al.*, Fusion Sci. Technol. **50**, 327 (2006).
[2] M. Yokoyama, *et al.*, Nucl. Fusion **47**, 1213 (2007).
[3] Y. Takeiri, *et al.*, Phys. Plasmas **10**, 1788 (2003).
[4] T. Shimozuma, *et al.*, Plasma Phys. Control. Fusion **45**, 1183 (2003).
[5] K. Ida, *et al.*, Phy. Rev. Lett. **91**, 085003 (2003).
[6] Y. Takeiri, *et al.*, Fusion Sci. Technol. **46**, 106 (2004).
[7] O. Motojima, *et al.*, Nucl. Fusion **47**, S668 (2007).
[8] O. Kaneko, *et al.*, *Proc. 16th Int. Conf. on Fusion Energy 1996 (Montreal, 1996)* Vol. 3 (Vienna, IAEA) p. 539.
[9] Y. Takeiri, *et al.*, Nucl. Fusion **46**, S199 (2006).
[10] M. Osakabe, *et al.*, this conference.
[11] Y. Takeiri, *et al.*, Nucl. Fusion **45**, 565 (2005).
[12] Y. Takeiri, *et al.*, Nucl. Fusion **47**, 1078 (2007).
[13] K. Nagaoka, *et al.*, this conference.
[14] M. Yoshinuma, *et al.*, this conference.
[15] S. Kubo, *et al.*, Plasma Phys. Control. Fusion **47**, A81 (2005).