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Electric Field Measurement and Limiter Experiment on LHD

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Abstract

Transition from the ion root to the electron root in neutral beam heated plasmas was observed in the Large Helical Device for the first time. The measured values of the radial electric field were found to agree well with those estimated by neoclassical theory. The pedestal configuration, which is characterized by a high edge temperature gradient, was observed in LHD plasma, resulting in the improvement of the energy confinement. A radially movable limiter was inserted into the pedestal region. The pedestal configuration was still observed at the edge region bounded by the limiter without changing its width and gradient, and no confinement degradation was observed.

Keywords:

radial electric field, electric field transition from the ion root to the electron root, radially movable limiter, pedestal configuration

1. Introduction

The Large Helical Device (LHD) [1-4] is the largest superconducting heliotron type device with $l = 2/m = 10$ continuous helical coils and three pairs of poloidal coils. The major and minor radii of the plasma are 3.5–3.9 m and 0.6–0.65 m, respectively. The maximum magnetic field strength is 2.89 T at the magnetic axis of $R_{ax} = 3.6$ m. The available heating powers are 4.2 MW from two Neutral Beam Injections

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(NBIs), 1.4 MW from one Ion Cyclotron Range of Frequency (ICRF) heating system, and 0.9 MW of Electron Cyclotron Resonance (ECR) heating with six gyrotrons. Achieved plasma parameters are as follows; (a) peak electron temperature of $T_e(0) = 4.4$ keV at $\langle n_e \rangle = 5.3 \times 10^{18}$ m^{-3} and $P_{abs} = 1.8$ MW, (b) peak energy confinement time of $\tau_E = 0.3$ s, $T_e(0) = 1.1$ keV at $\langle n_e \rangle = 6.5 \times 10^{19}$ m^{-3} and $P_{abs} = 2.0$ MW, (c) higher stored energy of W_p = 880 kJ, (d) the highest beta value achieved in helical systems of $\langle \beta \rangle = 2.4$ % at 1.3 T. The achieved energy confinement time in LHD is systematically higher than that predicted by the International Stellarator Scaling 95 (ISS95) [5] by up to a factor of 1.6 and is comparable with ELMy H-mode confinement capability in tokamaks. This improvement is attributed to configuration control and to the formation of a high edge temperature (pedestal) [6]. In this regard, the radial electric field (E_r) is one of the key parameters in helical systems for high temperature plasma confinement because neoclassical theory suggests a reduction of a helical ripple loss and an improvement of an energy confinement by the radial electric field. In general, the ambipolarity relationship has multiple solutions since the electron and the ion are usually in different regimes of collisionality. The electric field caused mainly by the ion flow is called the ion root (negative E_r) and the electric field caused mainly by the electron flow is called the electron root (positive E_r) [7]. As the absolute value of the positive E_r (electron root) is larger than that of the negative E_r (ion root), more improvement of the energy confinement is expected by a transition of the radial electric field from the ion root (negative E_r) to the electron root (positive E_r). The electron temperature profiles are measured with a multi-channel YAG Thomson scattering system [8] and electron density profiles are derived from a multi-channel FIR laser interferometer [9] measurement using Abel inversion. The transition of the radial electric field from the ion root to the electron root has been observed in neutral beam heated plasmas with ECR heating [10] in the Compact Helical System (CHS) [11]. Non-thermal electrons heated perpendicularly by the ECR easily escape through the loss-cone. In such case, the transition was triggered by the enhancement of electron loss. In LHD, the transition without the enhancement of electron loss, as described above, has been observed in neutral beam heated plasmas without ECR heating. The general trends in the observations are in accordance with the prediction of neoclassical theory.

An improvement in the overall energy confinement can be attributed to a reduction of electron thermal transport in the outer region of the plasma resulting in sharp temperature gradient [12]. A radially movable limiter was inserted to this pedestal region in order to investigate the pedestal formation [13]. Pedestal formation was observed without changing the width at the edge region bounded by the limiter maintaining its width. No serious degradation of energy confinement was observed in the limiter experiment.

2. Electric Field Measurement

The radial electric field (E_r) is derived from the poloidal and toroidal rotation velocity and pressure gradient of the Neon impurity ions by means of radial force balance. The poloidal and toroidal rotation velocity and the pressure gradient of the Neon impurity ions are measured with charge exchange spectroscopy (CXRS) [14] at the mid plane in LHD (vertically elongated cross section). The transition from the negative E_r (ion root) to the positive E_r (electron root) was observed at electron densities below 1.0×10^{19} m^{-3}. Figure 1 shows the radial electric field profiles for three magnetic axis positions; (a) $R_{ax} = 3.6$ m (inward shift), (b) $R_{ax} = 3.75$ m (standard), (c) $R_{ax} = 3.9$ m (outward shift). The electron densities in each measurement are also shown in Fig. 1. By shifting the magnetic axis inward, the neoclassical transport is expected to decrease [15]. The critical electron densities for the transition from the electron root to the ion root are obtained from the density-scan experimental results; (a) 0.3×10^{19} m^{-3} (inward shift), (b) 0.7×10^{19} m^{-3} (standard), (c) 0.8×10^{19} m^{-3} (outward shift). This is due to the differences in the ratio of edge ion temperature to electron temperature [16]. With $T_e > T_i$ the transition from the ion root to the electron root occurs at a higher collisionality. The edge radial electric field increases sharply up to 15 kV/m in the electron root as the electron density decreases. On the other hand, the edge radial electric field in the ion root increases gradually up to –5 kV/m over a wide range of electron density of 1.0–3.0 $\times 10^{19}$ m^{-3} [16]. Small radial electric field is observed in the plasma core region. The critical electron density for the transition in the case of inward shift is lower than that in the case of outward shift. The behavior of the radial electric field and their absolute values in both the electron and ion roots are in good agreement with predictions of neoclassical theory. The critical electron density required for the transition also agrees well with neoclassical predictions. The reduction of ion thermal diffusivity by the electric field associated

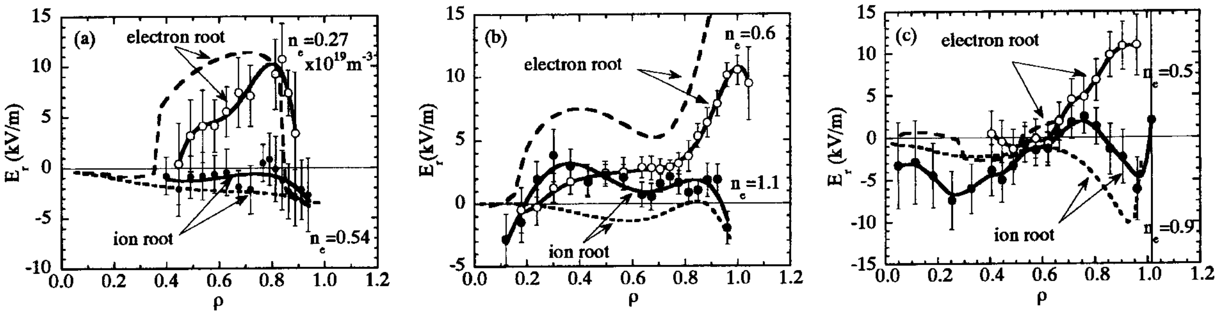

Fig. 1 Radial profiles of the radial electric field in case of (a) R_{ax} = 3.6 m (inward shift configuration), (b) R_{ax} = 3.75 m (standard configuration), and (c) R_{ax} = 3.9 m (outward shift configuration). Dashed lines show neoclassical predictions.

with the transition from ion root to electron root was observed for the plasma with R_{ax} = 3.75 m [16].

3. Limiter Experiment

A pedestal configuration, which has a high temperature gradient at a plasma edge [6], is observed in LHD. Usual plasma discharges in LHD have been carried out with an open helical divertor configuration. To compare pedestal formation in an open divertor discharge with that in a limiter discharge and to investigate a dependence of confinement on plasma minor radius, a radial movable limiter was installed at 7.5L lower port of LHD. Figure 2 shows a schematic figure of the limiter and magnetic flux surfaces with R_{ax} = 3.6 m. The limiter head, which was made of carbon (IG430U) with high thermal conductivity, was inserted into the plasma at the high field side (under the helical coil winding) as shown in Fig. 2. The limiter position is controlled remotely with accuracy of 0.5 mm.

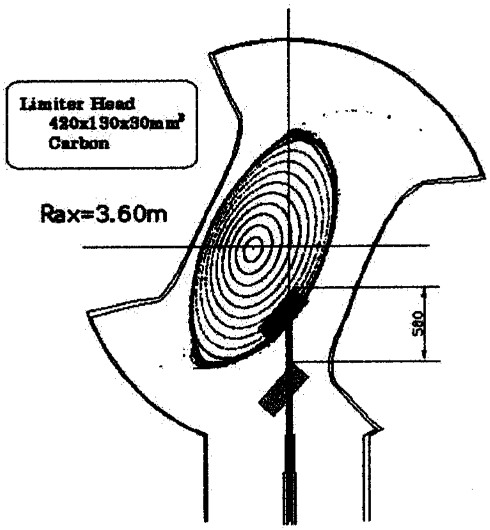

Fig. 2 Schematic figure of movable limiter.

Figure 3 compares the radial profiles of electron

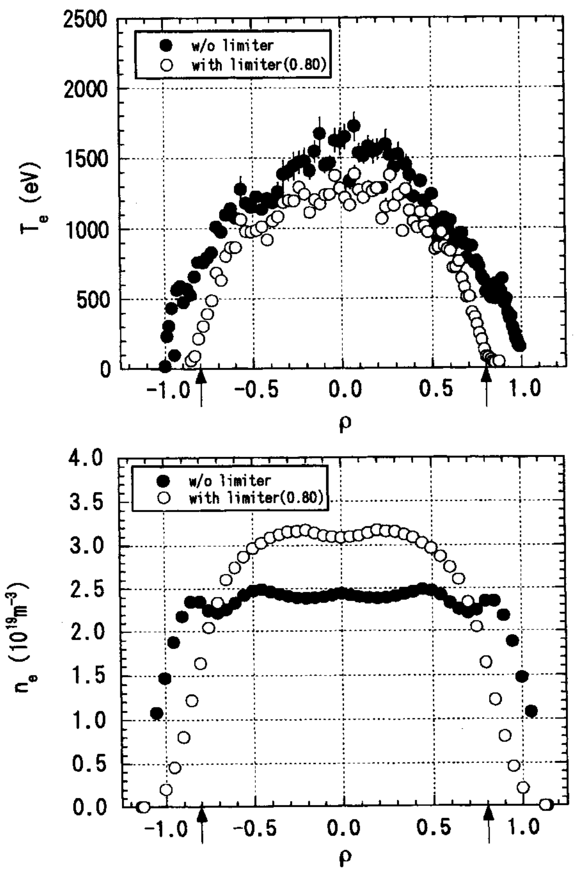

Fig. 3 Comparisons of electron temperature and density profiles with and without limiter. The equivalent limiter position is indicated by arrow.

density and temperature in the open divertor discharge and limiter discharge. The arrows in this figure indicate the equivalent limiter position. The electron temperature profile was bounded well by the limiter but the plasma density profile was not bounded well by the limiter. In the case of the open divertor discharge, however, the plasma density exists in an ergodic region ($\rho > 1.0$), which surrounds closed magnetic surface region. A clear change of the electron temperature gradient can be seen at $\rho \sim 0.85$ in the open divertor discharge and $\rho \sim 0.6$ in the limiter discharge. A high temperature gradient is also maintained in the limiter discharges.

Dependences of the central electron temperature (T_{e0}), electron temperature at the pedestal knee position (T_e^{ped}), line averaged electron density ($<n_e>$), pedestal width ($\Delta\rho_{ped}$), and the temperature gradient at the pedestal region ($T_e^{ped}/\Delta\rho_{ped}$) on various limiter positions are shown in Fig. 4. The position of $\rho = 1.2$ in this figure means the farthest limiter position. Namely, these data are in the open divertor discharges. The electron temperature at the pedestal knee and the pedestal width remain constant with limiter position. As a result, a high temperature gradient in the pedestal region is also maintained in this experimental range.

It was shown that the formation of a pedestal configuration led to a good energy confinement in divertor discharges [14] and the pedestal was similar to the internal thermal barrier in a Tokamak [6]. As the pedestal formation is observed in the limiter discharge, good energy confinement is expected. Figure 5 shows the normalized energy confinement time according to the ISS95 scaling at various limiter positions. The ISS95 scaling is expressed as follows [5]:

$$\tau_E^{ISS95} = 0.079 a_p^{2.21} R_p^{0.65} P_{tot}^{-0.59} <n_e>^{0.51} B_t^{0.83} \iota_{2/3}^{0.4}$$

where a_p and R_p are plasma minor and major radii, respectively, and P_{tot} total absorbed power, $<n_e>$ line averaged electron density, B_t magnetic field strength, and $\iota_{2/3}$ rotational transform at radial position of $2/3a_p$. An enhancement factor of 1.1±0.3 over the predictions of the ISS95 scaling was observed at every limiter position. In this experiment, plasma parameters other than a_p do not change much and their dependences on τ_E

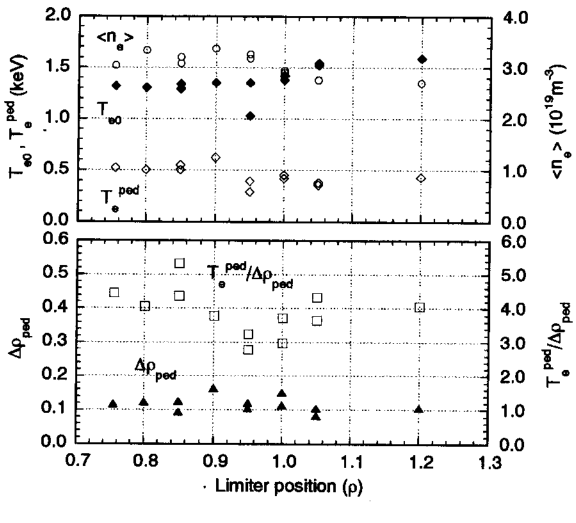

Fig. 4 Dependence of the central electron temperature T_{e0}, the pedestal electron temperature T_e^{ped}, average electron density $<n_e>$, pedestal width $\Delta\rho_{ped}$, and the temperature gradient at pedestal $T_e^{ped}/\Delta\rho_{ped}$ on limiter position. The limiter position is expressed in flux coordinate, and $r = 1.2$ means the farthest position.

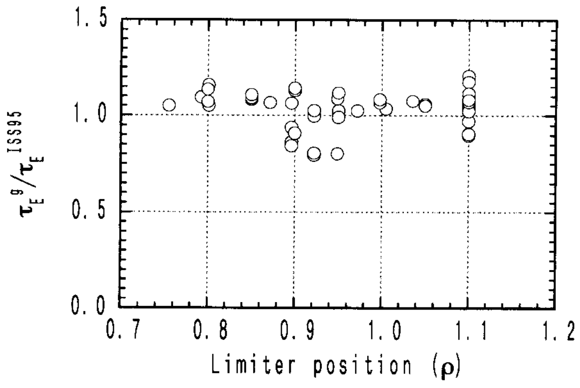

Fig. 5 Comparison of the energy confinement time with the ISS95 scaling.

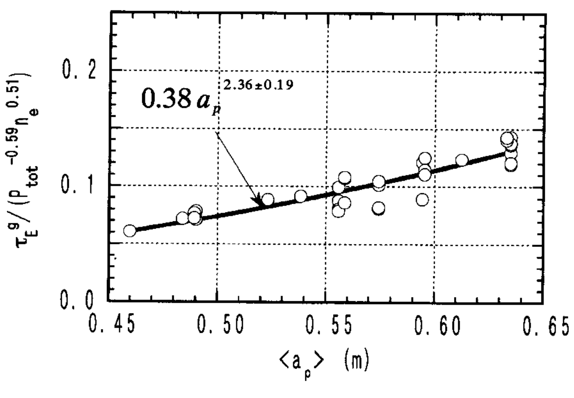

Fig. 6 Dependence of the energy confinement time on the plasma minor radius.

are weaker than that of a_p. According to this scaling, the change of a_p from 1.0 to 0.75 corresponds to a 44 % change of τ_E. Figure 6 shows the dependence of the energy confinement time on the plasma minor radius. To exclude the contributions of the density and the absorbed power, the energy confinement time τ_E^g is normalized by $P_{tot}^{-0.59}<n_e>^{0.51}$. Solid line indicates the resulting curve of a regression analysis. This result agrees well with the ISS95 scaling within an error bar. So these results suggest the dependence of the energy confinement time on the plasma minor radius is in accordance with the ISS95 scaling.

4. Summary

The transition from the ion root to the electron root in neutral beam heated discharges was observed in the Large Helical Device for the first time without ECR heating. The measured values of the radial electric field were found to be in good agreement with those estimated by neoclassical theory. The measured high electric field associated with the transition from the ion root to the electron root and the reduction of ion thermal diffusivity supports the thesis that the helical ripple loss is suppressed by the radial electric field. The radially movable limiter was inserted into the peripheral region of the LHD plasma. The pedestal configuration was observed both in the open divertor discharges and limiter discharges without degradation of the energy confinement time was observed. This is circumstantial evidence that the pedestal configuration contributed to the high energy confinement. Dependence of the energy confinement time on the minor radius is in agreement with that of ISS95 scaling ($a_p^{2.21}$).

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