Control of the radial electric field shear by modification of the magnetic field configuration in LHD

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Abstract.
Control of the radial electric field, E_r, is considered to be important in helical plasmas, because the radial electric field and its shear are expected to reduce neoclassical and anomalous transport, respectively. In general, the radial electric field can be controlled by changing the collisionality, and positive or negative electric field have been obtained by decreasing or increasing the electron density. Although the sign of the radial electric field can be controlled by changing the collisionality, modification of the magnetic field is required to achieve further control of the radial electric field, especially producing a strong radial electric field shear. In the Large Helical Device (LHD) the radial electric field profiles are shown to be controlled by the modification of the magnetic field by 1) changing the radial profile of the helical ripples, ε_h, 2) creating a magnetic island with an external perturbation field coil and 3) changing the local island divertor coil current.

1. Introduction

Since the radial electric field and its shear was recognized to play an important role on the improvement of transport, the control of the radial profile of the radial electric field is one of the important tools to improve confinement in toroidal plasmas. In tokamak plasmas, the transition of the radial electric field is observed to be associated with the transition from L-mode to H-mode plasma[1,2]. In stellarator and Heliotron plasmas, the transition of the radial electric field is triggered by the neo-classical non-ambipolar ion and electron flux, and the radial electric field becomes positive (in the electron root) when the plasma collisionality is low enough, while it is negative (in the ion root) at higher collisionality. Associated with transition of radial electric field from negative (ion root) to large positive (electron root), the reduction of electron thermal diffusivity is observed in CHS, Wendelstein-7AS and LHD plasmas [3-7]. Therefore it is important to investigate the technique to control radial electric field profiles and understand the physics behind them. In this paper, the control of the radial electric field profiles and the effect of radial electric field on transport especially particle/impurity transport are described.

2. Control of Radial electric field

The Large Helical Device (LHD) is a Heliotron device (poloidal period number L = 2, and toroidal period number M = 10) with a major radius of R_{ax} =3.5 – 4.1 m, an average minor radius of 0.6 m, magnetic field up to 3T , and heating neutral beam with negative ions with a beam energy of 150 – 180 keV. Typically two-third of the total beam energy is deposited to the electrons, because of this high beam energy. The radial electric field (E_r) is derived from the poloidal and toroidal rotation velocity and pressure gradient of Neon impurity measured with charge exchange spectroscopy[8] at the mid plane in LHD (vertically elongated cross section) using radial force balance. The radial force balance equation can be expressed as $E_r = (en_I Z_I)^{-1}(?p_I/?r) - (v_\theta B_{\phi?} - v_\phi B_\theta)$, where $B_{\phi?}$ and $B_{\theta?}$ are the toroidal and poloidal magnetic field and Z_I, n_I, p_I are the ion charge, density and pressure of the measured impurity, respectively.

The Large Helical Device (LHD) has n/m=1/1 external perturbation coils. The size of magnetic island can be controlled up to 10cm by changing the current of the perturbation coils. The spatial resolution of the measurements of the radial electric field using the charge exchange spectroscopy is determined by the length of integration of the signal along the line of sight within the beam width of the neutral beam. The spatial resolution becomes poor near the plasma center and relatively good near the plasma edge and it is +/− 1.5cm at the R=4.05m. In this experiment, radial profiles of electron density are measured with FIR and CO2 laser interferometer, while the electron temperature profiles are measured with a YAG Thomson scattering system and ion temperature profiles are measured with charge exchange spectroscopy. The total radiation power is measured with a bolometer.

2.1. Helical ripple strength

Since the radial electric field in LHD is determined by the ambipolar condition of ion flux and electron flux that are trapped in the helical ripples, a change in magnitude and radial profiles of helical ripples will be most straightforward tool to control radial electric field[9]. In LHD, the radial profiles of helical ripples can be modified by a shift of the magnetic axis from 3.5m to 3.9m.

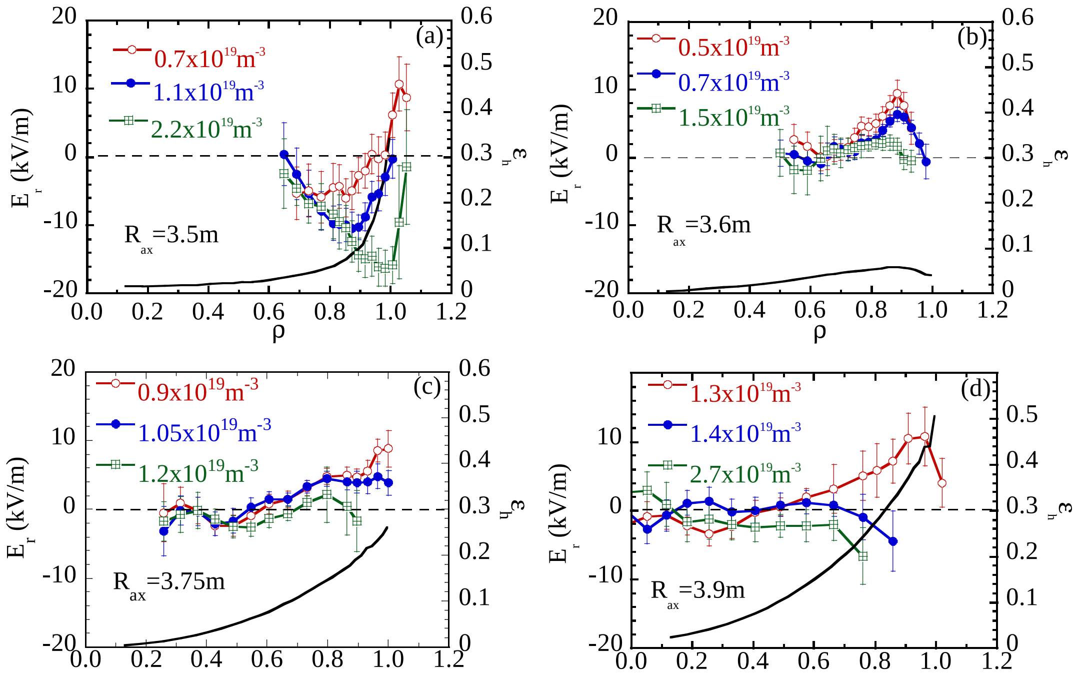

Fig.1 Radial profiles of radial electric field, E_r and helical ripple ε_h for plasmas with various magnetic axis, R_{ax} of 3.5m, 3.6m, 3.75m, and 3.9m.

Figure 1 shows the radial profiles of the radial electric field for the ion root (large neoclassical flux with negative E_r in the high collisionality regime), electron root (small neoclassical flux with positive E_r in the low collisionality regime) and the transition regime (between ion root and electron root) for various configurations with different helical ripple profiles. When the helical ripple increases gradually towards the plasma edge (R_{ax}=3.75m, 3.9m), the electron root region extends to half of the plasma minor radius and the radial electric field shear produced is relatively weak. However, when the helical ripple increases sharply at the plasma edge (R_{ax}=3.5m), the electron root region is localized at the plasma edge

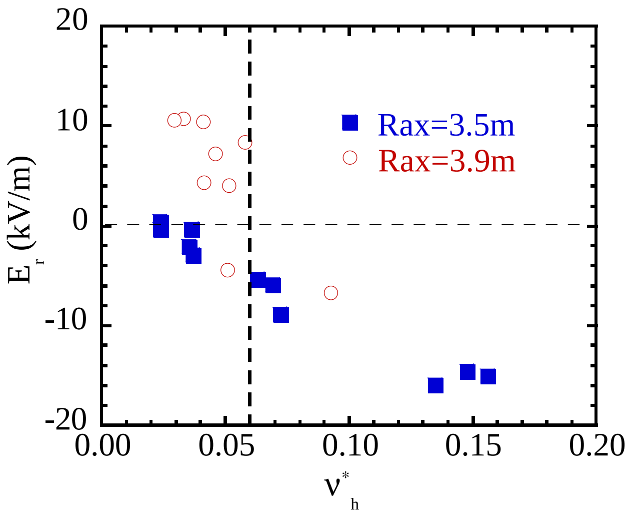

Fig.2 Radial electric field as a function of collisionality normalized by the bounce frequency of helically trapped particles.

and strong radial electric field shear is produced. When the magnitude of the helical ripple is suppressed to a low level (R_{ax}=3.6m), the transition region of the radial electric field is located at ρ = 0.9, not at the plasma edge, because there is no increase in the helical ripple at the plasma edge in this configuration. These results show that a strong magnetic field shear can be obtained at the plasma edge by shifting the magnetic axis inward rather than shifting the magnetic axis outward, where the achievement of electron root itself is relatively easy (even with higher collisionality).

The electron density at the transition from ion root to electron root is 0.7 x $10x^{19}m^{-3}$ for the plasma with the magnetic axis of 3.5m, while it is 1.3 x $10^{19}m^{-3}$ for the plasma with the magnetic axis of 3.9m. The difference in critical electron density can be explained by the differences in the magnitude of helical ripples. As seen in Fig.2, the transition from ion root to electron root occurs when the collisionality normalized by the bounce frequency of helically trapped particles decreases below 0.06 regardless of the magnetic axis. This characteristic is consistent with the prediction by neoclassical theory[10,11]. In the plasmas with large helical ripples (R_{ax}=3.75m, 3.9m), a reduction of the thermal diffusivity is observed associated with the transition from the ion root to the electron root. However, there is no reduction of the thermal diffusivity observed associated with the transition in the plasma with small ripples (R_{ax}=3.5m, 3.6m), because neoclassical transport is always smaller than anomalous transport.

2.2. Magnetic island

Formation of the magnetic island is considered to be a useful tool to produce the strong radial electric field shear at the boundary of the magnetic island, since the plasma flow is expected to be damped inside the magnetic island. The size of the magnetic island in the plasma is normally smaller than that expected by the vacuum magnetic field because the healing effect[12]. This healing effect becomes larger in the plasma with lower collisionality[13,14]. The island structure of the radial electric field was investigated for the medium density plasma in the ion root[15] and radial electric field shear are observed at the boundary of the magnetic island [Fig3(a)]. This raised the question as to whether radial electric field shear can be produced in the electron root plasma, where the collisionality might be too low to produce a magnetic island.

Figure 3(b) show the radial electric field profiles for various currents of the n/m=1/1 external coils for the electron root and the ion root plasmas. When the perturbation field is small enough there is no magnetic island structure observed. The radial electric field is positive for the electron root plasma and negative for the ion root plasmas. As the perturbation field is increased, a clear magnetic island structure appears in the radial profiles of the radial electric field. The radial electric field becomes zero at the magnetic island (R= 4.00m - 4.08m), both for the electron root and ion root plasmas. Relatively large radial electric field shear is produced at both boundaries of the magnetic island for the plasma in the ion root. The radial electric field shear is more pronounced at the outer boundary of the magnetic island for the plasma in the electron root, because the radial electric field is close to zero at the location of the inner boundary of the magnetic island (R=4.0m) even for the plasma without a magnetic island.

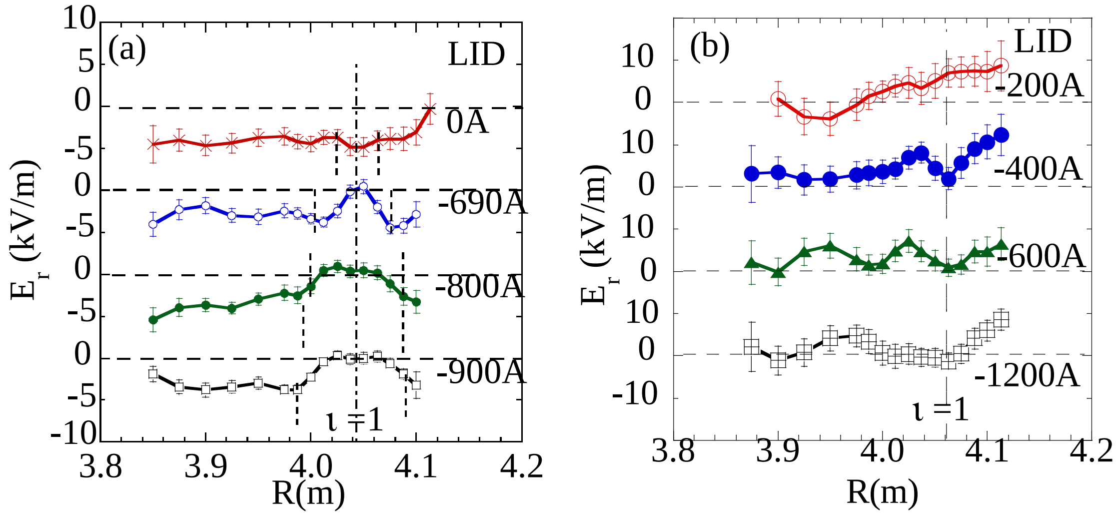

Fig.3 Radial profiles of radial electric field with magnetic island for the plasma (a) in the ion root and (b) in the electron root.

Because the radial electric field shear may exist at the boundary of the magnetic island, the transport barrier may start near the boundary of magnetic island. In fact the magnetic island contributes to the formation of electron internal transport barrier (ITB) near the threshold power of ECH for the transition to ITB in LHD[16]. Therefore it is considered that the magnetic island may contribute to the formation of the ion internal transport barrier, which has not been observed in LHD yet.

Figure 4 shows the radial profiles of the electric field, electron density, ion temperature and electron temperature for the plasma with pellet injection and with and without a magnetic island. The combination of pellet injection and magnetic island causes an improvement of the ion transport at the inner side of the magnetic island. Before the pellet injection, electron density profiles are almost flat and there is no radial electric field shear observed. After the pellet injection, the strong radial electric field shear appears only for the plasma with a magnetic island, not for the plasma without a magnetic island. This radial electric field shear is due to the increase of the electron density and ion temperature gradients as seen in Fig.4 (b) and (c). Although the increase of ion temperature gradients suggests improvement of the ion transport, the improvement is transient. It is noted that there is no improvement of the electron transport because there is almost no change in the electron temperature gradients after the pellet injection between the plasmas with and without a magnetic island. When there is no magnetic island, no radial electric field shear and no internal transport barrier are created even with pellet injection. This experiment shows the importance of the radial electric field shear appearing at the boundary of the magnetic island in the formation of an internal transport barrier.

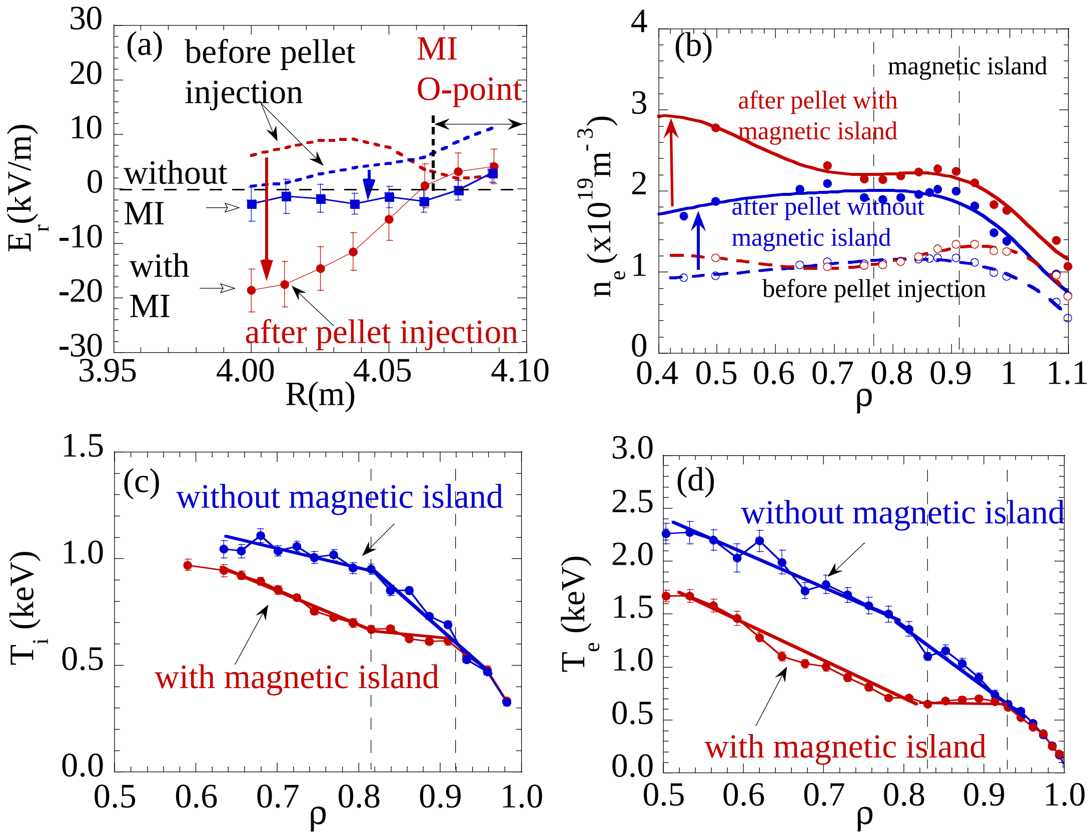

Fig.4 Radial profiles of (a) radial electric field (b) electron density (c) ion temperature (d) electron temperature for the plasma with pellet injection with and without a magnetic island.

3. Role of Radial electric field on particle transport

The radial electric field itself is expected to affect the particle transport especially impurity transport [17-19], which is in contrast to the radial electric field shear effect on the energy transport. In the CHS experiment, the impurities tend to accumulate at the plasma axis and the impurity and electron density profiles tend to peaked in plasmas with negative electric field, while the impurity is exhausted and impurity and density profiles are hollow in plasmas with positive electric field[20]. Therefore it is expected that the positive electric field should contribute to suppress the influx of impurities and prevent the radiation collapse.

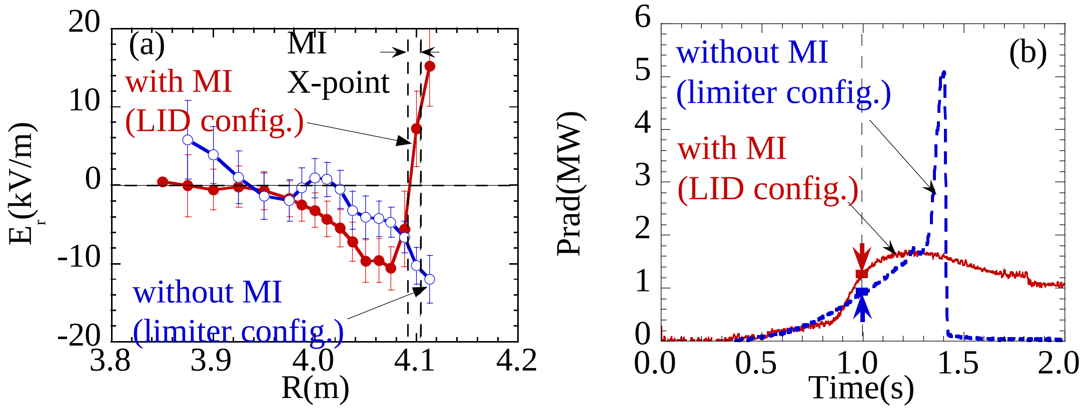

Fig.5 (a) Radial profiles of radial electric field with a magnetic island (LID configuration) and without a magnetic island (limiter configuration) and (b) time evolution of the radiation power.

Figure 5 shows the radial profile of the radial electric field for the plasma with a limiter configuration and a Local Island Divertor (LID)[21] configuration, where a part of the magnetic island is connected to a local island divertor head. In the divertor (LID) configuration, a large positive electric field with a sharp radial electric field shear is observed, while the radial electric field is negative for the plasma with a limiter configuration. The sign of the radial electric field changes from negative to positive by crossing the X-point of the magnetic island. This positive electric field is considered to be produced by the electron loss along the magnetic field line toward the LID limiter head. Since this positive electric field is located in the region of the direct electron loss, the radial electric field shear in this region could not contribute to the improvement of the electron transport. However, the radial electric field at the edge plays a role in preventing the influx of impurities into the plasma with an LID configuration. As seen in Fig5(b), the plasma shows radiation collapse when the edge radial electric field is negative in the limiter configuration. On the other hand, the impurities are exhausted when the edge radial electric field is positive in the LID configuration.

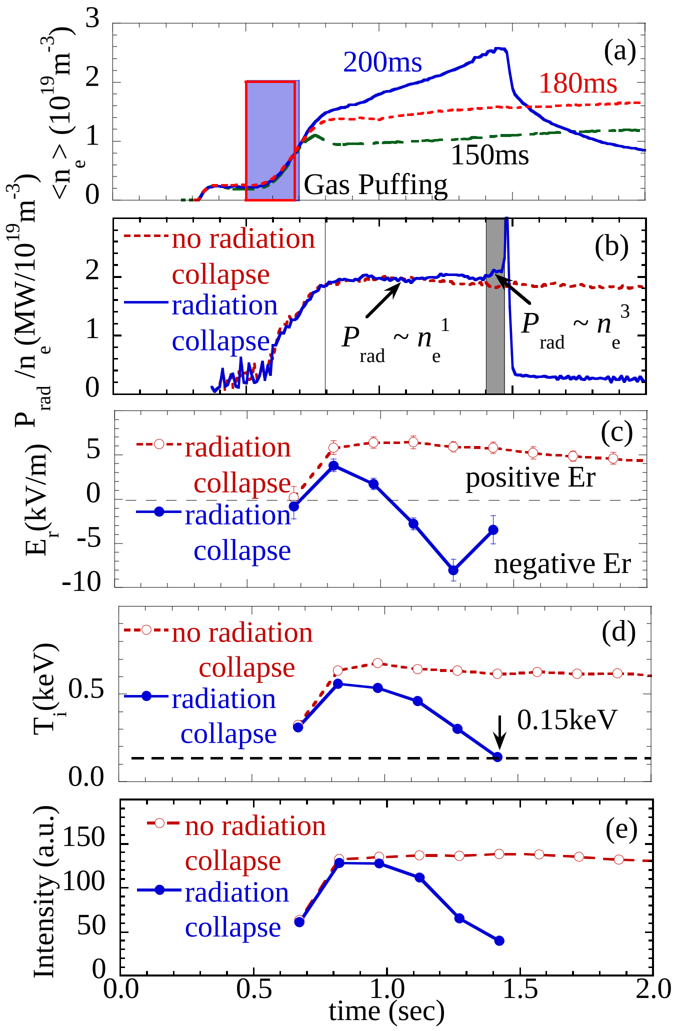

Fig.6 Time evolution of (a) line averaged electron density (b) normalized total radiation power (c) radial electric field (d) ion temperature and (e) NeX intensity at ρ = 0.89 for the discharges with and without radiation collapse.

The role of positive radial electric field in preventing the impurity flux is also observed in experiments in the plasma with radiation collapse. When the short Ne puff is applied to the plasma in the early phase of the discharge, there are two type of discharges; one is steady state discharge without radiative collapse, the other is a transient discharge resulting radiative collapse even when the Ne puff is already turned off [Fig6(a)]. The 10% increase of Ne puff (from 180ms pulse width to 200ms pulse width) early in the discharge causes this difference. Therefore there should be a feedback mechanism in the radiation collapse related to the increase of the electron density. The temperature dependence of the cooling coefficient, which results in the sharp increase of radiation power proportional to n_e^3[22] , can not explain the spontaneous gradual increase of radiation power proportional to n_e^1 at well before the radiation collapse(t = 0.8 – 1.4sec). There should be a feedback mechanism relating particle and/or impurity transport and radial electric field.

As seen in Fig.6, the radial electric field starts to be more negative 0.5 sec before the radiative collapse. The radial electric field becomes more and more negative until the radiative collapse. The change of radial electric field to more negative is due to the increase of collisionality (increase of electron density and decrease of temperature). When the radial electric field becomes more negative, the negative radial electric field causes an increase of the impurity flux, because the exhausting effect by positive radial electric field disappears. In the discharge without radiation collapse, the radial electric field remains positive with no increase of electron density and radiation power. The ion temperature shows a significant drop down to 150eV just before the radiation collapse. Associated with decreasing temperature, the NeX intensity also drops because the fully ionized neon decreases by the recombination process. These drops are not observed in the discharge without radiation collapse. These data shows there are two steps in the discharge towards the radiative collapse. Until just before the radiative collapse (t < 1.27 sec), there is no significant drop of temperature. The feedback process between the negative radial electric field and the increasing electron density should be the most important process. Just before the radiation collapse (t > 1.27 sec), the feedback process between the decreasing temperature and increasing cooling rate also is considered to be important.

Figure 7(a)(b) show the time slice of the radial electric field and the ion temperature in the discharge, which is terminated by radiative collapse. The negative electric field is localized near the plasma edge at $\rho = 0.8 – 0.9$. Just before the radiative collapse (t = 1.43 sec), the negative radial electric field region extends to more inside of the plasma ($\rho < 0.7 – 0.8$) and the edge radial electric field becomes less negative at t = 1.42s. Although the negative electric field is localized in the narrow region ($\Delta\rho = 0.1$), the drop of ion temperature is observed in the wide region. These observation shows the positive electric field is quite important to avoid the radiation collapse and consistent with the experimental results in the LID configuration, where the impurity influx is shielded by the strong positive electric field near the X point of magnetic island.

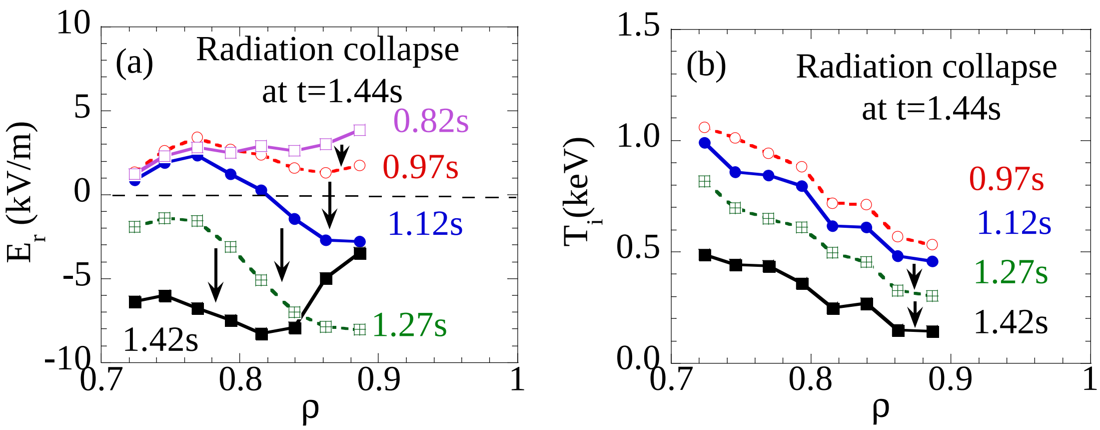

Fig.7 Radial profiles of (a) radial electric field and (b) ion temperature in the discharges with radiation collapse.

4 Discussions

The strong shear of the radial electric field is demonstrated to be produced inside the plasma by controlling the helical ripple and the magnetic topology (magnetic island and LID configuration) to trigger an internal transport barrier and reduce impurity influx. The radial electric field shear is demonstrated to be controlled by the modification of the helical ripple associated with the shift of the magnetic axis, while the sign of the radial electric field is controlled by the collisionality. The magnetic configuration with a sharp gradient in the helical ripple is considered to be more appropriate for creating the strong radial electric field shear. The magnetic island produces the radial electric field shear at the boundaries of the magnetic island and hence contributes to trigger the formation of an internal transport barrier in the electron root plasma. The transient improvement of the ion transport in the ion root is also observed after the pellet injection with the assistance of n/m=1/1 island. This is due to the fact that the increase of the electron density gradient by pellet injection is transient and there is not enough particle source to sustain the density gradient. This improvement is expected to be sustained in the steady state by increasing ion heating power and beam fueling using a low energy beam of 40 keV, which is planned to be installed in LHD in the near future to increase the heating power to ions.

In addition to the temperature dependence of the coiling rate, the feedback mechanism in which negative electric field causes an increase of the density, which results in a more negative electric field, is crucial to the process of radiative collapse. The role of radial electric field is found to be quite important to prevent the influx of impurities and avoid the radiative collapse. The positive electric field observed in the LID configuration is considered to an important role for impurity shielding. Therefore the improvement of thermal transport and impurity exhaust are achieved by the control of radial electric field profiles in LHD.

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References

[1] R.J.Groebner, K.H.Burrell, and R.P.Seraydarian, Phys. Rev. Lett. 64, (1990) 3015
[2] K.Ida, et. al., Phys Rev Lett 65 (1990) 1364.
[3] A.Fujisawa, et. al., Phys Rev Lett 82 (1999) 2669.
[4] U.Stroth, et. al., Phys Rev Lett 86 (2001) 5910.
[5] T.Shimozuma et al., Plasma Phys Control Fusion 45 (2003) 1183.
[6] K.Ida, et. al., Phys Rev Lett 91 (2003) 085003.
[7] Y.Takeiri et al., Phys. Plasma 10 (2003) 1788
[8] K.Ida, S. Kado, Y. Liang, Rev. Sci. Instrum. 71 (2000) 2360
[9] K.Ida, et. al., Phys Rev Lett 86 (2001) 5297.
[10] L.M.Kovrizhnykh L.M. Nucl. Fusion 24 (1984) 435
[11] M.Yokoyama, et al., Nucl. Fusion 42 (2002) 143.
[12] K.Narihara, et al., Phys Rev Lett 87 (2001) 35002
[13] N.Ohyabu et al., Phys Rev Lett 88 (2002) 55005
[14] Y.Nagayama et al., this conference
[15] K.Ida, et al., Phys Rev Lett 88 (2002) 015002
[16] K.Ida, et. al., Phys plasmas 11 (2004) 2551
[17] K.Ida, et. al., Phys Rev Lett 68 (1992) 182
[18] Y.Nakamura, et. al., Nucl Fusion 43 (2003) 219.
[19] K.Ida, et. al., Plasma Phys Control Fusion 45 (2003) 1931
[20] K.Ida et. al., Phys Plasmas 08 (2001) 1
[21] A.Komori, T.Morisaki, et al., this conference.
[22] B.Peterson, et al., this conference