Simultaneous Realization of High Density Edge Transport Barrier and Improved L-mode on CHS

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Abstract An edge transport barrier (ETB) formation and an improved L-mode (IL mode) have been simultaneously realized in high density region ($\bar{n}_e \sim 1.2 \times 10^{20} m^{-3}$) on Compact Helical System (CHS). When the ETB is formed during the IL mode, the density reduction in the edge region is suppressed by the barrier formation. As a result of the continuous increasing of the temperature by the IL mode, the stored energy during the combined mode increased up to the maximum stored energy ($W_p \sim 9.4kJ$) recorded in CHS experiments. The plasma pressure in the peripheral region increases up to three times larger than that of the L-mode, and the large edge plasma pressure gradient is formed accompanying the pedestal structure. That is caused by the anomalous transport reduction that is confirmed from the sharp drop of the density fluctuation in the edge region. The neutral particle reduction in the peripheral region and the metallic impurity accumulation in the core plasma are simultaneously observed during the high density ETB formation.

1. Introduction

The improved confinement of the helical plasma has been investigated during the past years. The realization of the improved confinement for a high density plasma is especially required to develop a fusion reactor of the helical device as well as the tokamak device. First observation of the confinement improvement of the helical device in the high density region was a High density H-mode in W7-AS[1]. Recently, the internal diffusion barrier has been observed with producing a super dense core on LHD[2]. These results demonstrate that the high density operation is favorable to realize the fusion reactor of the helical device compared to the tokamak device.

In the tokamak experiments, the core confinement improvement with the peaked electron density has been found, which is called improved L-mode[3]. The IL mode (reheat mode) has been also observed in the CHS experiment[4, 5]. This mode is initiated by shutting off fueling after strong gas-puffing. During the IL mode, the density profile is peaked, and the temperature in the peripheral region ($\rho(r/a) > 0.6$) considerably increases transiently. The electron temperature in the peripheral region increases resulting from a suppression of neutral particle density causing the charge exchange loss. The IL mode is also similar to the high T_i mode[6] of the helical plasma, which is caused by the radial electric field that is created by an ion root transition. The IL mode is observed in the high density region, however, the peripheral density continues to decrease after the fueling stop, and the stored energy rapidly goes down.

On the other hand, the ETB of CHS has various characteristics similar to the tokamak experiments[7, 8]. A clear spontaneous drop of H_α emission followed by the increase of line-averaged electron density has been observed at the L-H transition, which accompany a density gradient increase in the edge region ($\rho \sim 0.9$). The NBI power that is required for the barrier formation in the limiter-plasmas is similar to the tokamak divertor H-mode scaling [7, 9]. However, there are several different points from the tokamak experiments. In the CHS experiments, the ETB is always ELM free, therefore degradation by ELMs has not been observed[7]. In the tokamak experiments, the clear pedestal structure has been observed, while the structure of the barrier is unclear in CHS experiments. In the previous CHS experiments, the H-factor increases during ~ 20 ms after the transition, however, it gradually decreases subsequently with a density increase, because the confinement improvement is degraded. If the performance degradation of the ETB does not occur with the density increase, the enhanced confinement is achieved in the high density region.

Accordingly, the simultaneous realization of both modes are favorable for the enhanced confinement in the high density region. However, it requires an extending the ETB performance to the higher density region. In addition, there is the issue of whether the ETB and the IL mode are compatible modes or not. Recently, the edge transport barrier during the IL mode has been observed and extends the operational regime of ETB to the high density region on CHS. The results have been preliminarily reported in [10]. The detailed characteristics of the high density edge transport barrier (HDETB) formation during the IL mode is described in [11].

Increased understandings for the combined mode are described in this paper. First, experimental conditions and a global behavior of the HDETB plasma are described. In addition, a relation of the IL mode to the peaking factor is discussed. Secondly, confinement characteristics of the HDETB are discussed. Thirdly, a spatial structure of the improved region of the HDETB is discussed. Fourthly, we show an evidence of an impurity accumulation during the HDETB. Fifthly, we show results of density fluctuation measurements to discuss an anomalous transport of the HDETB. Finally, we summarize this paper.

2. Global behavior of high density edge transport barrier during improved L mode

Experiments are performed on CHS, which is a medium-sized heliotron type device with a periodicity of (l,m) = (2,8). The major and averaged minor radii are 1.0 and 0.2 m, respectively. The all experiments described in this paper performed under a condition of the limiter configuration, in which the last closed flux surface is limited by an inner wall. The working gas is hydrogen. The magnetic field strength is $1.86T$, of which is a highest value of the CHS experiment and is favorable to realize the IL mode. However, the ETB has not been observed in the CHS experiments under $B_T = 1.86T$ and the standard configuration of $R_{ax} = 92.1cm$. Accordingly, the experiment is carried out under the outer shifted magnetic configuration ($R_{ax} = 94.9cm$), because the outer shift reduce the required power threshold for the ETB formation[7].

The global behavior of the simultaneous realization of both the IL mode and the HDETB is shown in Fig.1. A Blue zone indicates a period of a first standard ETB formation, a green zone indicates a period of IL mode without HDETB, and a red zone indicates a period of HDETB formation during IL mode. The line averaged density is measured with an HCN interferometer, and the radiation is measured with a pyroelectric detector. The time evolution of the peaking factors $T_e(0)$, $T_e(0)/\langle T_e\rangle$, and $n_e(0)/\langle n_e\rangle$ are derived from profile measurements with a multipoint YAG Thomson scattering system, where $\langle T_e\rangle$,$\langle n_e\rangle$ are the volume averaged value. The stored energy is measured with the diamagnetic loop. In the high density region ($n_e > 2 \times 10^{19} m^{-3}$), the value has a good agreement with a kinetic value that is derived from the YAG Thomson scattering measurement.

The target plasma is produce by a 54.5GHz gyrotron, and then the plasma is sustained by the co-injected two NBIs of which the total power is 1.6 MW. In CHS experiments, the co-injection is favorable for the ETB formation which is similar to the tokamak experiments[7]. First, the standard ETB is formed from 45 ms by the strong gas-puff. The plasma density in peripheral region increases by the particle confinement improvement by the barrier formation[7]. Then the core density increases with the density profile peaking as show in Fig.1(h) due to maintaining particle supply by the gas-puff. At 95 ms, the ETB formation is broken, which is denoted by the H_α signal sharply increase as shown in Fig.1(e). That is because the electron density exceeds the upper limit which is determined by the density dependence of the power threshold ($P_{threshold} \propto n_e^{0.4}$). As shown in Fig.1(b), the increase of the stored energy is saturated during the standard ETB, and then the stored energy gradually decreases with the density increase. After the L-mode transition, the stored energy further decreases due to the temperature decrease in the peripheral region, which result form the increase of the radiation as show in Fig.1(f). Because the behavior of the radiation is almost same as that of the H_α signal, this radiation increase is cased by the neutral particle increase in the peripheral region resulting from the disappearance of the barrier.

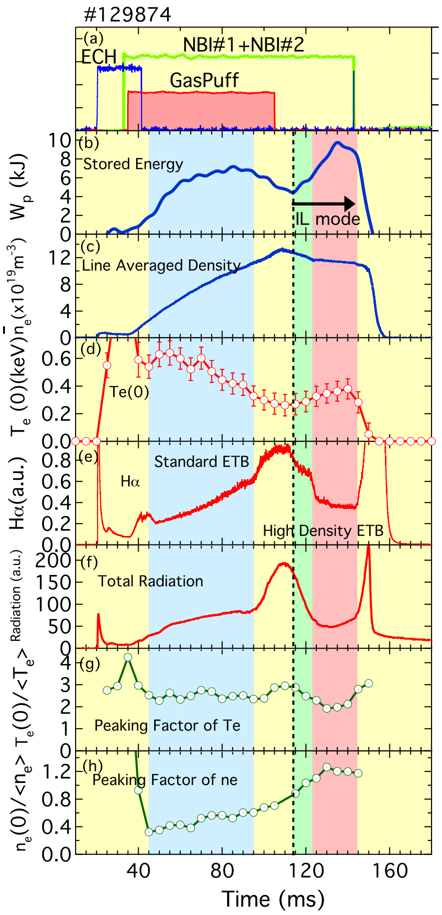

FIG. 1: *Global behavior of HDETB plasma: (a) injection timings of NBI and ECH, (b) stored energy W_p, (c) line averaged density, (d) $T_e(0)$, (e) H_α, (f) total radiation (g) $T_e(0)$, and (h) $n_e(0)/\langle n_e\rangle$.*

After the gas-puff stop at 100 ms, the electron temperature increases with the radiation reduction. On the contrary, the plasma density, as shown in Fig.1(c), rapidly decreases. The onset of the IL mode is denoted by the increased plasma stored energy from 115 ms due to the temperature increase in the peripheral region, which is denoted by the temperature profile is broadened, as is shown in Fig.1(g). The density profile continues to be peaked during the IL mode, and the plasma radiation continues to reduce resulting from the reduction of the peripheral neutral density. Though the similar phenomena of the confinement improvement with the density peaking has been observed in the tokamak experiments, the radiation reduction in the peripheral region does not correspond to the IL mode (RI mode) of the tokamak experiments[12]. When the density decreased below the upper limit of the ETB formation ($\bar{n}_e \sim 1.2 \times 10^{20}\mathrm{m}^{-3}$), the ETB is reformed and the plasma confinement is improved form L to H-mode during the IL mode, which is denoted by the H_α reduction at 123 ms. And then, the density reduction is suppressed, as show in Fig.1(c), and the density peaking is stopped and then the profile shape is maintained, because the particle confinement in the edge region is improved by the barrier formation. Consequently, the plasma confinement is improved by the synergistic effect of the simultaneous realization of both the IL mode and the HDETB. This HDETB is realized in a high density region where the enhanced confinement by the standard ETB have not been observed. As a result of the continuous increase of the temperature by the IL mode, the stored energy increased up to $\sim 9.4kJ$, which is larger than that of the first standard ETB period (~ 7 kJ). After achieving the peak value of the stored energy, the energy is slightly reduced (134 ms), because the temperature is reduced in the peripheral region during the HDETB formation due to the confinement degradation by the radiation increase, as is shown in Fig.1(f).

3. Confinement of high density edge transport barrier plasma

An H-factor is estimated using the ISS04 CHS/Heliotron/ATF scaling (τ_{ISS04})[13]. This scaling low has a good agreement with the CHS L-mode confinement compared to the ISS95 scaling. The confinement time is estimated by a formula of $\tau_E = W_p/(P_{dep} - dW_p/dt)$ where τ_E is the confinement time, W_p is the stored energy and the P_{dep} is the deposited NBI Power. The deposited NBI power is estimated by the empirical low of the CHS experiment. In the CHS experiments, the H-factor ($H = \tau_E/\tau_{ISS04}$) of the NBI plasma without the ETB does not exceed one. The time evolution of the H-factor is shown in Fig.2(a). An evolution of the H-factor with the line averaged density is also shown in Fig.2(b).

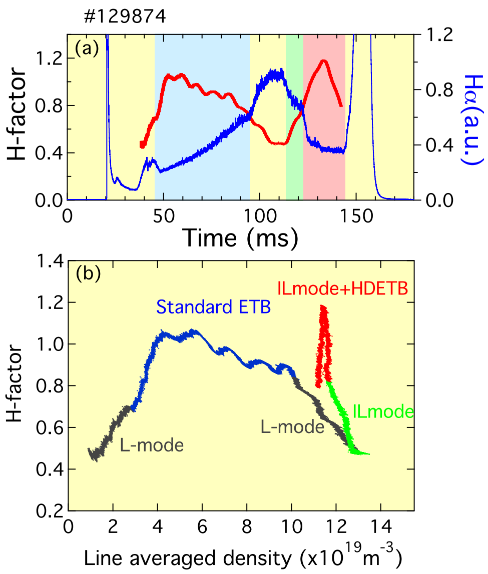

FIG. 2: *(a) Time evolution of H-factor based on ISS04 CHS/Heliotron/ATF scaling. (b) H-factor as a function of line averaged density.*

After the first transition to the H-mode, the H-factor increases from 0.75 to 1.05. However, the increase of the H-factor is immediately suppressed and then decreases ~ 10 ms after the transition. This observation is a typical characteristic of the standard ETB in CHS[7]. It is noted that the confinement of the L-mode after the standard ETB is clearly degraded compared to the H-mode due to the increase of the radiation, as shown in Fig.1(f). In contrast, the H-factor increases from 0.5 to 0.85 by the IL mode with the density decrease. When the HDETB is formed during the IL mode, the H-factor increases up to ~ 1.3 with maintaining the almost steady-state plasma density. When typical case of the IL mode without the ETB, the H-factor is rapidly reduced by the density reduction. Thus, improved confinement is realized in the high density region ($\bar{n}_e \sim 1.2 \times 10^{20}\mathrm{m}^{-3}$) by the simultaneous realization of both the HDETB and the IL mode. The H-factor value of ~ 1.3 might be underestimated, because the CHS L-mode confinement is degraded by the outward shift[14]. The experiments are performed for the configuration of R_{ax} = 94.9 cm, while the ISS04 scaling is derived from the data in the standard configuration of the $R_{ax} = 92.1cm$.

4. Profiles and pedestal formation of high density edge transport barrier plasma

Detailed plasma profiles on the HDETB transition during the IL mode were measured with the multipoint YAG laser Thomson scattering system. Figure 3 shows density, temperature, and pressure profiles for the same shot as is described in section 2, respectively. The 4 profiles for different timing that represent the characteristics are plotted: the profiles before the fueling stops (100 ms), before the IL mode (110 ms), during the IL mode without the HDETB (120 ms), and during the IL mode with the HDETB (130 ms) are plotted in figure 3. To clear the variation of the profiles, $\triangle T_e(10ms)/T_e$(e) and $\Delta n_e(10ms)/n_e$(f) are also plotted.

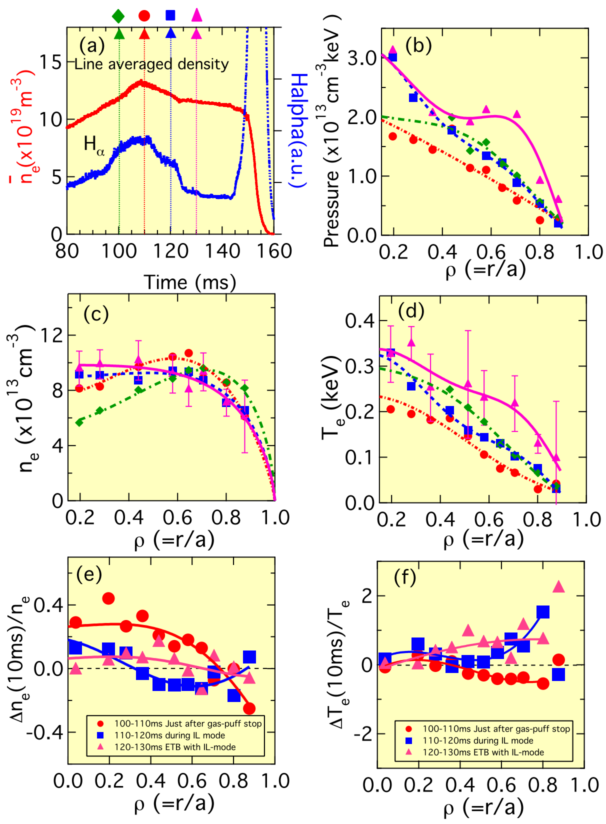

FIG. 3: *Profiles of HDETB: (a) timing of measurement with H_α and line averaged density, (b) pressure, (b) electron density (c), electron temperature. (d) and (e) are $\Delta n_e/n_e$ and $\Delta T_e/T_e$ of 10 ms intervals, respectively.*

After the timing of the gas-puff stop, the density profile is rapidly peaked during the first 10 ms, while the electron temperature decreases in the peripheral region, because the plasma radiation does not decrease in this period as shown in Fig.1(f). However, the electron temperature increases by the IL mode from 110 ms with the radiation reduction, although the electron density continues to decrease in the peripheral region. Because the central density continues to increase, the density profile becomes peaked during the IL mode. In contrast, because the peripheral temperature increases during the IL mode, an inflection point appears in the temperature profile at $\rho \sim 0.5$, and the pedestal structure is formed, as is shown in figure 3(d). The estimated penetration length of the neutral particles to the plasma from the plasma surface is approximately in terms of $\Delta\rho \sim 0.4$, thus the region of the temperature increase almost coincides with the region of reduced neutral particles.

From the onset (123 ms) of the HDETB formation, the reduction of the density is suppressed and the density profile shape is maintained during the HDETB formation. This result shows that the diffusion of the peripheral plasma was blocked by the transport barrier formation in the edge region. In addition, the electron temperature further increase by the IL mode in the peripheral region. The previous results of the ETB experiments on the CHS show that the edge density gradient increases with the confinement improvement just after the L-H transition. However, the plasma confinement is degraded ~ 20 ms after the transition, because the peripheral electron temperature decreases with the peripheral density continuous increase[7], though the H_α signal is maintained at a small level. In contrast, the plasma pressure in the peripheral region at 140 ms increases up to three times larger than that of the first standard ETB. Consequently, the pressure gradient increase, and the pedestal structure is also formed in the pressure profile, as shown in figure 3 (b), thus the increase of the stored energy is mainly caused by the increase of the plasma pressure in the peripheral region. The deposited NBI power to the HDETB plasma during the IL mode is almost same as that in the final timing of the first standard ETB (~ 90 ms), because the densities in both timings are almost same. Therefore, the global plasma confinement is improved by the HDETB formation during the IL mode.

These features are similar to the results of the ASDEX tokamak experiments[15]. However, the temperature and density profiles become broader and a pedestal develop during the IL mode in the ASDEX experiment, because an edge transport barrier is developing during the IL mode. In contrast, the density profile is peaked during the IL mode before the H transition in CHS experiment, because the density clearly exceeds the threshold power for the barrier formation.

5. Impurity accumulation by high density edge transport barrier

An impurity accumulation in the plasma central core is observed during the HDETB. The experiment is performed for a discharge that have almost same parameters as described in the section 2 (B_T = 1.86T, R_{ax} = 94.9cm). The plasma is heated by the two co-NBIs from 30 ms to 105 ms. The timing of the gas-puff stop is 105 ms. The result of the total radiation and H_α are shown in Fig.4(b). Fig.4(c) shows the edge and the central channel of a line averaged signal of an AXUV (absolute extreme ultraviolet) photodiode measurement[16]. The minimum normalized minor radii for the edge and center chords are 0.85 and 0.06, respectively. The temporal behavior of the total radiation and the AXUV signals are clearly different during the IL mode with the HDETB. On the contrary, the temporal behavior during the first standard ETB has same tendency, because the sensitivity of the AXUV detectors is reduced in wavelength longer than 6 nm[16]. Accordingly, the AXUV signals mainly reflect the behavior of the metallic impurities (e.g., Fe, Ti). In contrast, the total radiation measured with the pyroelectric detector mainly reflect the behavior of the oxygen in the peripheral region judging from the ionized energies of the impurities. Consequently, the metallic impurity is accumulated in the core region during the HDETB.

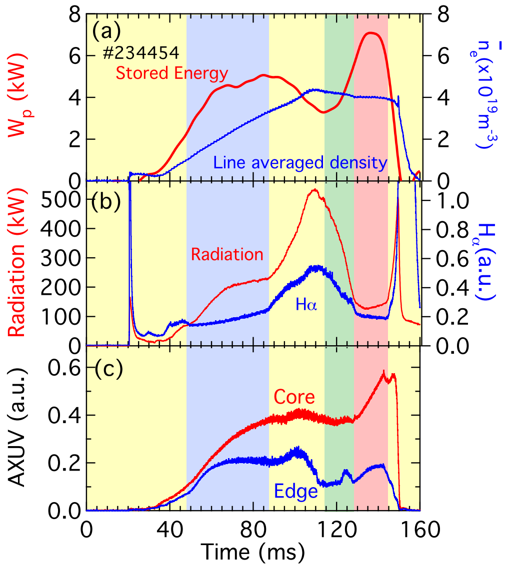

FIG. 4: *Time evolution of the radiation for HDETB: (a) W_p and line averaged density, (b) total radiation and H_α, (c) AXUV signal of center and edge chord.*

The impurity behavior of the IL mode with the HDETB (125 - 145 ms) are clearly different from that of the IL mode without the HDETB period (115 ms-125 ms). The H_α signal of the IL mode without the HDETB shows the large reduction of the neutral particles in the peripheral region, as show in Fig.4(b). The total radiation also shows the reduction of the impurity oxygen. On the contrary, the metallic impurity accumulation in the plasma core is slight as is shown in 4 (c). In contrast, the considerable impurity accumulation to the plasma central core is observed after the HDETB transition. However, the amount of the neutral particles of the hydrogen and the oxygen in the peripheral region is maintained at low level, though the reduction is suppressed by the barrier formation as is shown in 4 (b). Accordingly, the rapid degradation of the plasma confinement during the HDETB might be caused by the impurity accumulation. It is noted that the same tendency of the impurity accumulation is observed during the first standard ETB. The line averaged AXUV signal of the core shows the accumulation of the impurity in the plasma central core, because the AXUV signal of the edge is saturated. However, the behavior of the neutral particles has an opposite tendency to that of the HDETB. The total radiation and the H_α signal show the increase of the neutral particles of the hydrogen and the oxygen in the peripheral region.

6. Behaviors of density fluctuations during high density edge transport barrier formation

Figure 5 shows the results of the density fluctuation measurement with a YAG laser phase contrast interferometer (YAG PCI)[17] and a beam emission spectroscopy (BES)[18]. In the

YAG PCI measurement, the fluctuations are integrated along the YAG laser path passing through the mid-plane of the plasma cross-section. The measurable wavelength and the frequency of the fluctuation are $20kHz < f < 312.5kHz$, $4mm < \lambda < 30mm$, respectively[17]. The wave-number direction of the fluctuation component is poloidal (k_θ), because the YAG PCI can measure the perpendicular component to the laser path. The BES can measure the local fluctuation with a resolution of $\Delta\rho \sim \pm 0.15$, and a temporal resolution is $1\mu s$[18].

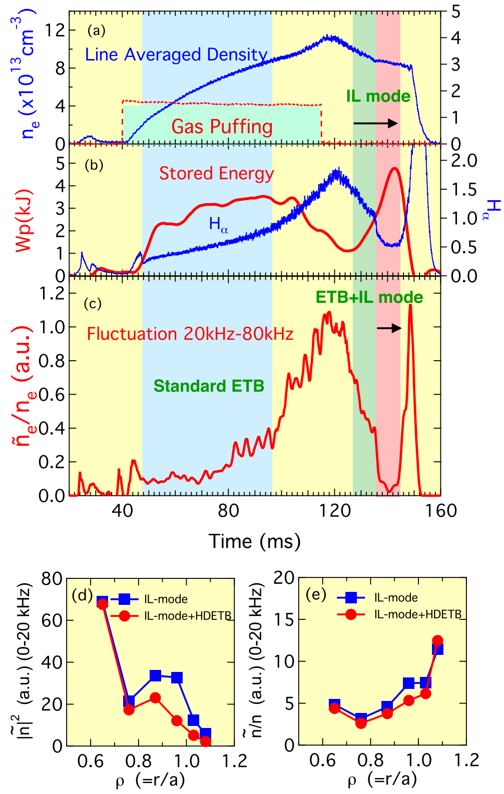

FIG. 5: *Result of density fluctuation measurement. (a) Density and gas-puffing (b) Stored energy and H_α. (c) $\tilde{n}_e/n_e$ of fluctuation with a YAG PCI, (d)$|n_e|^2$ profile, and (e)$\tilde{n}_e/n_e$ profile with BES.*

In the first standard ETB phase, the fluctuation is reduced a few micro seconds before the L-H transition. After then, the fluctuation gradually increases with the density increase, and the increase of the stored energy is saturated because of the confinement degradation, as shown in Fig.5. Accordingly, the confinement degradation during the first ETB is caused by the turbulence that induce the anomalous transport. In contrast, when the plasma enter the IL mode that is denoted by the stored energy re-ascending, the reduction of the fluctuation is enhanced accompanying the H-factor increase. When the ETB is formed during the IL mode, the density reduction is reduced (figure 5(a)) and the fluctuations sharply drop to the level of the onset of the first standard ETB period, though the plasma density during the IL mode is considerably larger than that of the first ETB phase. The wavelength of the reduced fluctuation is from 10 mm to 30 mm and that frequency is from 20 kH to 80 kHz. The reduction of the fluctuations is maintained during the HDETB period. Therefore, the anomalous transport is considerably suppressed in the high density region by the simultaneous realization of both the IL mode and the HDETB.

Though the fluctuation measured with the YAG PCI is the line averaged one along the central chord, the same results are confirmed by a HCN scattering measurement, which can detect the local scattering signal from the edge region ($\rho \sim 0.9$). The BES can measure the fluctuation of low frequency ($< 20kHz$) [18] in the peripheral region. The fluctuations of the low frequency region are also reduced during the HDETB with the IL mode around $\rho \sim 0.9$ compared to the IL mode as shown in 5(c),(d).

The improved plasma confinement by the ETB during the IL mode is related to the reduction of anomalous transport. As is previously mentioned, the neutral particle density of the HDETB in the peripheral region is lower than that of the standard ETB. In addition, the confinement in the standard ETB period is gradually degraded resulting from the radiation increase. These results suggest that the expansion of the ETB operation regime to the high density is related to the neutral particles in the peripheral region.

7. Summary

The simultaneous realization of both the HDETB and the IL mode is demonstrated on CHS. The peripheral temperature increases while maintaining the plasma density in the edge region by the ETB formation. The pedestal like structures of the temperature and the pressure are observed in the peripheral region. The larger peripheral pressure and the pressure gradient than that of the standard ETB is achieved. The enhanced confinement regime is extended to the high density region ($\bar{n}_e \sim 1.2 \times 10^{20} \mathrm{m}^{-3}$) by the combined mode due to the reduction of the anomalous transport. The phenomena are related to the neutral particles in the peripheral region. The combined mode is the transit phenomenon which may be caused by the metallic impurity accumulation to the core plasma. The control of the impurity accumulation is a remaining issue to maintain the enhanced confinement.

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