Characteristics of high density edge transport barrier with reheat mode on CHS

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Abstract. Edge transport barrier (ETB) formation and a reheat mode have been simultaneously realized on the Compact Helical System (CHS). The new mode is induced by neutral particle reduction in the edge region, which is caused by shutting off fueling after a strong gas-puffing. When both the reheat mode and the ETB are simultaneously realized, the density reduction is suppressed by the ETB in the peripheral region, and the temperature continues to increase by the reheat mode. This mode provides an enhanced confinement in the high density region ($\bar{n}_e \sim 1.2 \times 10^{20} \text{m}^{-3}$) compared to the ETB formation without the reheat mode, because of a large suppression of an anomalous transport, which is confirmed with fluctuation measurements in the edge region.

1. Introduction

The realization of improved confinement for a high density plasma is important from the aspect of a helical device as a fusion reactor for the helical device, because high density operation is favorable for the helical devices compared to the tokamak devices[1]. However, it is difficult in the high density range to achieve an enhanced confinement. For example, an internal transport barrier of the helical devices that is formed by an ambipolar diffusion of neoclassical particle fluxes requires a low electron density ($5 \times 10^{18} \text{m}^{-3}$) [1]. On the contrary, the formation of the edge transport barrier (ETB) and a reheat improved confinement mode occurred in a high density range compared to the helical ITB [2, 3, 4, 5, 6].

The reheat mode is a confinement improvement mode similar to an improved L-mode that is observed in tokamak experiments. This mode is initiated by shutting off fueling after strong gas-puffing[5, 6]. During the reheat mode, the density profile shape is peaked, and the temperature in the edge region 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 reheat mode is also similar to the high $T_i$ mode[8] of the helical plasma, which is caused by the radial electric field that is created by an ion root transition. However, the reheat mode has a problem: the peripheral density continues to decrease after the fueling stops, and the stored energy rapidly goes down.

Meanwhile, the ETB improves the peripheral particle confinement by barrier formation. The ETB of CHS has a clear spontaneous drop of $H_{\alpha}$ emission followed by the increase of line-averaged electron density at the L-H transition. The quick density doubling ($< 100 \mu \text{sec}$) has been observed accompanying the density gradient increase in the edge region. The NBI power that is required for the barrier formation...
in the limiter-plasmas is similar to the tokamak divertor H-mode scaling [9, 2]. However, there are several different points from the tokamak experiments. In CHS experiments, the ETB is ELM free, therefore degradation by ELMs has not been observed[2]. In 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, which is the ratio of the experimental confinement time to the calculation from the stellarator confinement scaling, 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 occurred with the density increase, the enhanced confinement is achieved in the high density range.

Accordingly, the simultaneous realization of both modes are favorable for the enhanced confinement in the high density range. However, it requires an extending the ETB performance in the higher density range. In addition, there is the issue of whether the ETB and the reheat mode are compatible modes or not. Recently, the edge transport barrier (ETB) during the reheat mode has been observed on CHS. The results have been preliminarily reported in [7].

This paper describes the detailed characteristics of the high density edge transport barrier formation during the reheat mode. Secondly, we show the structure of the improved region with the YAG thomson scattering measurements. Thirdly, we show that the results of the fluctuation measurement with a YAG phase contrast interferometer and discuss the anomalous transport. Finally, we summarize this paper.

2. Global behavior of high density edge transport barrier formation during reheat mode

Experiments are performed on CHS, which is a medium-sized heliotron/torsatron-type device with a periodicity of (l,m) = (2,8). The major and averaged minor radii are 1.0 and 0.2m, respectively. Because CHS is equipped with two co-NBIs (maximum power of each NBI is 0.8MW) and two gyrotrons (53GHz, 106GHz), we can study plasma physical characteristics for a wide variety of input powers and heating methods. When the reheat mode with the ETB is observed, the peripheral temperature increases while maintaining the plasma density in the edge region by the ETB formation.

![Figure 1](image_url)

**Figure 1.** Global behavior of ETB plasma during reheat mode: line average density, $H_\alpha$ signal, radiation signal, and the stored energy $W_p$ are plotted with the injection timings of NBI and ECH. Blue zone indicates period of first ETB formation without reheat mode. Red zone indicates period of ETB formation during reheat mode.

Figure 1 shows the global behavior of the reheat mode discharge with an ETB. Although high field strength ($B_T = 1.86T$) is favorable for the reheat mode, the formation of the ETB under a high magnetic field condition is difficult, because the NBI power threshold of the ETB formation depends on the
magnetic field strength[2]. When the field strength increases, the NBI power threshold becomes larger. When the vacuum magnetic axis location \((R_{ax})\) shifts outwards, the threshold NBI power decreases. Accordingly, the experiment is carried out for the magnetic configuration of \(R_{ax} = 94.9\, \text{cm}\), which is larger than that of the standard configuration \((R_{ax} = 92.1\, \text{cm})\).

As shown in figure 1, the two co-NBIs (total power is 1.6 MW) are injected to the target plasma that is produced by a 54.5 GHz gyrotron. The ETB is formed below an upper density limit that is related to the NBI power threshold: the power threshold is determined by the heating power normalized with the electron density \((P/n_e)\) [2]. On the other hand, because the higher plasma density is required for a reheat mode, the plasma density is increased by gas-puffing until the ETB formation disappears once.

As shown in figure 1, the ETB is formed at 45 ms by the strong gas-puff, then the ETB disappears and the plasma returns to the L-mode again at 95 ms resulting from the electron density exceeding the upper limit, which is determined by the density dependence of the power threshold \((P_{\text{threshold}} \propto n_e^{0.4})\). The stored energy is saturated and decreases after the transition with the density increase. After the L-mode transition, the stored energy further decreases. Then, the plasma density, as shown in the middle of figure 1, decreased after the gas-puff stop at 105ms. The onset of the reheat mode is denoted by the increased plasma stored energy from 115 ms due to the temperature increase in the peripheral region. The plasma radiation continues to reduce resulting from the reduction of peripheral neutral density. When the density decreased below the upper limit \((\bar{n}_e \sim 1.2 \times 10^{20}\,\text{m}^{-3})\), the ETB is reformed in the edge region, which is denoted by the \(H_\alpha\) reduction at 123 ms. And then, the density reduction is suppressed, as show in figure 1, and accordingly, the particle transport in the edge region is reduced. It is noted that this ETB occurred in a high density range, where enhanced improvement by ETB formation with gas-puffing have not been observed. In the reheat mode without the ETB, the density in the edge region is rapidly reduced. In contrast, when the ETB is formed in the reheat mode, the density reduction is suppressed. Consequently, plasma confinement is improved by the synergistic effect of the simultaneous realization of both the reheat mode and the ETB. As a result of the continuous increase of the temperature by the reheat mode, the stored energy increased up to \(\sim 9.4\,\text{kJ}\), which is larger than that of the first ETB phase \((\sim 7\,\text{kJ})\). After that, the increase of the temperature is saturated, the density decreases gradually due to no fueling, thus the stored energy is slightly reduced (134 ms). The confinement is degraded by the radiation increase in the edge region.

An H-factor based on ISS04 CHS/Heliotron/ATF[10] scaling is estimated, in which the effect of \(\Delta W/\Delta t\) is taken into account. In the CHS experiments, the H-factor of the NBI plasma without the ETB is below one. When the ETB is formed during the reheat mode, the H-factor increases up to \(\sim 1.3\), which is larger than that during the L-mode just before the reheat mode. Thus, improved confinement is realized in the high density range \((\bar{n}_e \sim 1 \times 10^{20}\,\text{m}^{-3})\) by the simultaneous realization of both the ETB and the reheat mode. The H-factor value of \(\sim 1.3\) might be underestimated, because the CHS L-mode confinement is degraded by the outward shift[11]. The experiments are performed for the configuration of \(R_{ax} = 94.9\,\text{cm}\), while the ISS04 scaling is derived from the data in the standard configuration of the \(R_{ax} = 92.1\,\text{cm}\).

3. Pedestal structure during the high density edge transport barrier

Detailed plasma profiles on the ETB transition during the reheat mode were measured with the multipoint YAG laser Thomson scattering system. Figure 2 shows density, temperature, and pressure profiles for the typical discharge with the ETB formation during the reheat mode, respectively. The 4 profiles for different timing that represent the characteristics are plotted: the profiles before the fueling stops (100 ms), before the reheat mode (110 ms), during the reheat mode without the ETB (120 ms), and during the reheat mode with the ETB (130 ms) are plotted in figure 2.

The electron temperature and density in the L-mode continue to decrease during the first 10 ms after the timing of the gas-puff stop. However, the electron temperature increases inversely by the reheat mode from 110 ms, although the electron density continues to decrease in the edge region. Because the central density continues to increase, the density profile gradually becomes peaked during the reheat
The edge electron temperature decreases with the edge density continuous increase\(^2\), though the H-factor increase accompanies the L-H transition. However, the plasma confinement is degraded without the reheat mode, because the edge temperature increases during the reheat 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 2(b). 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 ETB formation, the reduction of the density is suppressed and the density profile shape is maintained during the ETB formation. This result shows that the diffusion of the peripheral plasma was blocked by the transport barrier formation. In addition, the electron temperature continues to increase by the reheat mode in the edge 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 \(\sim 20\) ms after the transition, because the edge electron temperature decreases with the edge density continuous increase\(^2\), though the \(H_a\) signal is maintained at a small level. In contrast, the plasma pressure in the edge region at 140 ms increases up to three times larger than that of the first ETB. Consequently, the pressure gradient increase, and the pedestal structure is also formed in the pressure profile, as shown in figure 2(c), thus the increase of the stored energy is mainly caused by the plasma pressure increase in the edge region. The deposited NBI power to the ETB plasma during the reheat mode is almost the same as that in the final timing of the first ETB (\(\sim 90\) ms), because the densities in both timings are almost the same. Therefore, global plasma confinement is improved by the ETB formation during the reheat mode.

### 4. Fluctuations during the high density edge transport barrier

Figure 3 shows the results of fluctuation measurement with a YAG laser phase contrast interferometer (YAG PCI)\(^1\). The fluctuations are integrated along the YAG laser path passing through the mid-plane of the plasma cross-section. The wave-number direction of the fluctuation component is poloidal (\(k_\theta\)), because the YAG PCI can measure the perpendicular component to the laser path. In the ETB phase without the reheat mode, 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 figure 3.

In contrast, when the plasma enter the reheat 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

![Figure 2. Density (a), Temperature (b) and pressure (c) profiles. Profiles before the gas-puff stop (100 ms), before the reheat mode (110 ms), during the reheat mode without the ETB (120 ms), and during the reheat mode with the ETB (130 ms) are plotted. Timings of the measurements are denoted (d).]
formed during the reheat mode, the density reduction is reduced (figure 3 (a)) and the fluctuations sharply drop to the level of the onset of the first ETB phase, though the plasma density during the reheat mode is considerably larger than that of the first ETB phase. The reduction of the fluctuations is maintained during the ETB phase. The same tendency of the fluctuations in the ETB plasma during the reheat mode is confirmed with the other measurements such as a HCN scattering measurement and beam emission spectroscopy[9, 13].

The improved plasma confinement by the ETB during the reheat mode is related to the reduction of anomalous transport. As show in figure 1, the $H_{\alpha}$ signal behavior shows that the neutral particle density of the ETB phase during the reheat mode is lower than that of the first ETB phase. In addition, the confinement in the first ETB phase is gradually degraded resulting from the radiation increase. These results suggest that the expansion of the ETB formation range to the high density is related to the neutral particles in the edge region. The viscosity of the edge plasma might decrease due to the neutral particle reduction, then the anomalous transport is suppressed by the $E \times B$ shear flow in the edge region.

5. Summary
We have demonstrated the simultaneous realization of both a reheat mode and an edge transport barrier (ETB) on CHS. The profile measurements show that a pedestal-like structure is created in the temperature and the pressure profiles in the edge region. Consequently, the peripheral plasma pressure becomes larger than that of the ETB without the reheat mode. The ETB during the reheat mode shows the compatibility of both modes in the high density range ($n_e \sim 1.2 \times 10^{20} \text{m}^{-3}$), where the confinement improvement by the ETB without the reheat mode has not been observed. The new mode provides enhanced confinement in the high density region due to the reduction of anomalous transport that is confirmed by the fluctuation measurement with the YAG PCI.

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