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Progress of Confinement Physics Study in Compact Helical System

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Abstract. Large progress in the confinement improvement study in CHS was made for the internal transport barrier (ITB) and H-mode discharges with the edge transport barrier (ETB). For ITB, precise measurement of ion temperature gradient profile and the direct measurement of turbulent particle flux were made. For ETB study, edge fluctuations were measured with four different diagnostics and it was confirmed that the turbulence was suppressed by the ETB formation. The poloidal flow was measured and the creation of the strong electric field was confirmed for the H-mode discharges. H-mode with a high plasma density was developed with the reheat mode operation technique.

1. Introduction

Compact Helical System (CHS) is a middle size (major radius is 1 m) stellarator with an aspect ratio 5. CHS is equipped with various profile diagnostics for plasma density, temperature, electric field, which are necessary to understand the transport physics in three-dimensional toroidal confinement. Recent progresses of CHS experiment include also the experimental observations of the correlations between the fluctuations and the transport barrier formations. Since the next-generation stellarators (advanced stellarators) have optimized magnetic configurations, the neo-classical transport is sufficiently low. Primary research targets of confinement must be the improvement in the anomalous transport, namely, the suppression of turbulence. Experimental observation of fluctuations and the study of its relation to the confinement improvement are very important for the progress of the confinement research in stellarators.

CHS has been leading the transport barrier physics study in stellarators. The internal transport barrier (ITB) was first found in CHS [1] for stellarator experiment with the fluctuation data measured by the heavy ion beam probe (HIBP) diagnostic. Although similar phenomena of raised electron temperature at the central region have been observed later in various stellarators, CHS has a unique feature of ITB effective for both electrons and ions [2]. The confirmation of the ion ITB was given by the new diagnostic of ion temperature gradient measurement. In addition, the measurement of the role of fluctuations at the transport barrier was improved and the suppression of turbulence-induced particle flux was demonstrated for the ITB formation.

H-mode was also found in CHS for the first time in stellarator experiment [3] simultaneously with the Wendelstein 7AS [4]. The characteristics and the structure of the edge transport barrier (ETB) formation have been studied continuously [5, 6]. In this paper, fluctuation and the plasma poloidal flow measurements at the H-mode transition are reported, which are important in the discussion of the turbulent transport and the mechanism of its suppression. The observation of impurity radiation lines and the development of their profiles during H-mode are also reported. Finally, a new type of H-mode with a high plasma density was found for the high magnetic field operation. Although previous H-mode discharges in CHS showed the edge density increase with little temperature increase, an increase of the edge pressure was significant at the transition with the raised edge electron temperature as well as density.

2. Progress in Studies of Internal Transport Barrier (ITB)

2.1. Ion Temperature Gradient Measurement for ITB Discharge

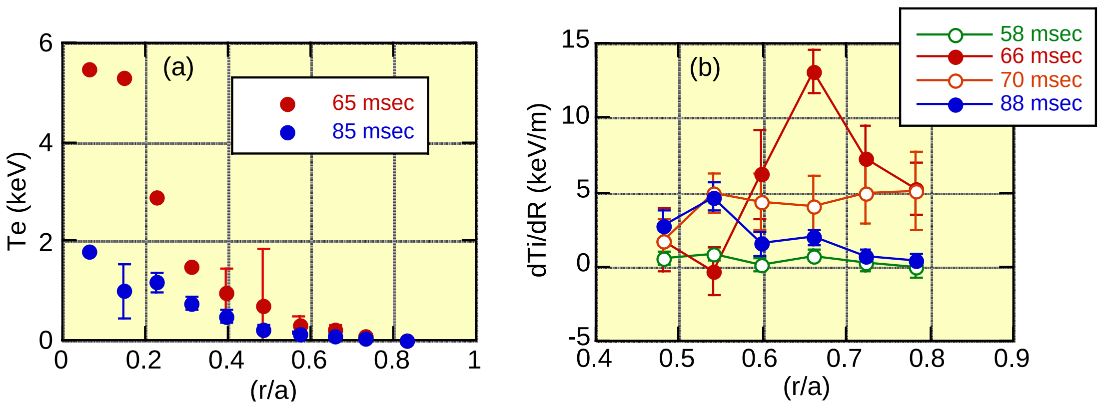

Fig. 1. Profiles of (a) electron temperature and (b) ion temperature gradient of ITB discharge. ITB is formed at 60 msec.

When ECH is applied to a low density NBI plasma in CHS, both the electron and ion temperature increase creating the steep temperature gradient region as transport barriers [2]. Two temperature profiles showed the different locations of the transport barriers (normalized minor radii (r/a) of foot points for electron and ion are 0.4 and 0.7, respectively). In order to locate the transport barrier for ions with higher precision, a new type of charge exchange spectroscopy was developed. In place of multi-point ion temperature profile measurement with multi-channel fiber optics, this system varies in time the observation point with a high luminosity and the fast time response, hence obtaining the temperature gradient with higher precision than the conventional profile measurement. The temperature gradient information is more directly coupled with the reduction of the transport. Figure 1 shows the spatial structure of the electron and ion temperature profiles with the ITB formation. ECH was applied on the NBI sustained plasma (Ne ~ 3×10^{18} m^{-3}) at 60 msec, which caused the ITB formation. Fig. 1(b) shows that the high temperature gradient is formed at 65 msec within a narrow region at (r/a) ~ 0.65, which is clearly different from the enhanced temperature gradient region in the electron temperature profile shown in Fig. 1(a). With the gradual increase of plasma density, the temperature gradient region expands and finally disappears at 100 msec. The normalized radius of ion transport barrier depends on the magnetic configuration (closer to the edge with the magnetic axis shifted outward) although the location of the electron transport barrier does not vary much. The physical mechanism determining the transport barrier location has not been understood.

2.2. Turbulence-induced Particle Flux Measurement with ITB Formation

In order to clarify the effect of ITB on the turbulent transport more directly, particle flux caused by the fluctuation was calculated based on the local measurements of density and potential fluctuations and their relative phases. Figure 2 shows the change of such turbulent particle flux at the transition. In this discharge, ITB disappeared at 70 msec due to the gradual increase of the density (back transition). The transition timing is given by the drop of the plasma potential inside the barrier shown by the green curve in the bottom figure. The upper figure shows a time variation of the turbulent flux spectrum (red color is outward flux and violet color is inward). The turbulent flux in the frequency range of 50 to 100 kHz is dominant. The change of flux with 70 kHz frequency is shown in the bottom figure with blue color, which shows abrupt increase in the outward direction at the transition.

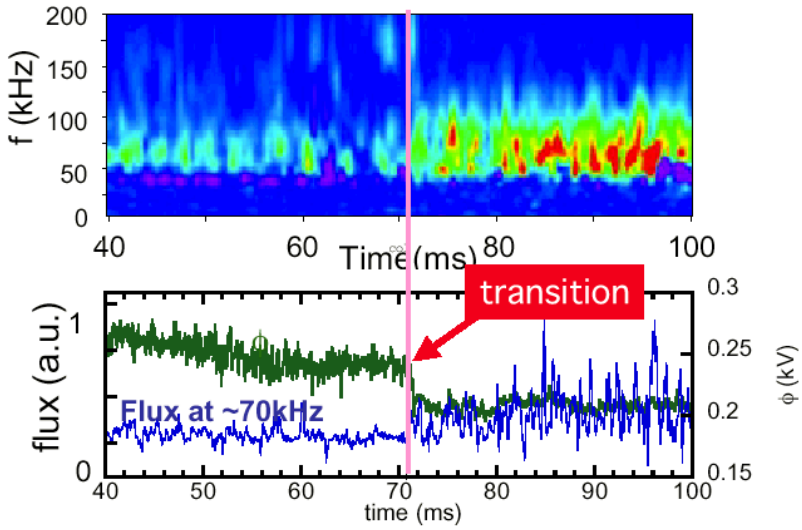

Fig. 2. (upper) Time variation of turbulent particle flux spectrum (red for outward and violet inward). (lower) Changes of potential (green) and outward flux (blue).

3. Progress in Studies of Edge Transport Barrier in Middle Density

3.1. Basic Characteristics of H-mode Discharges

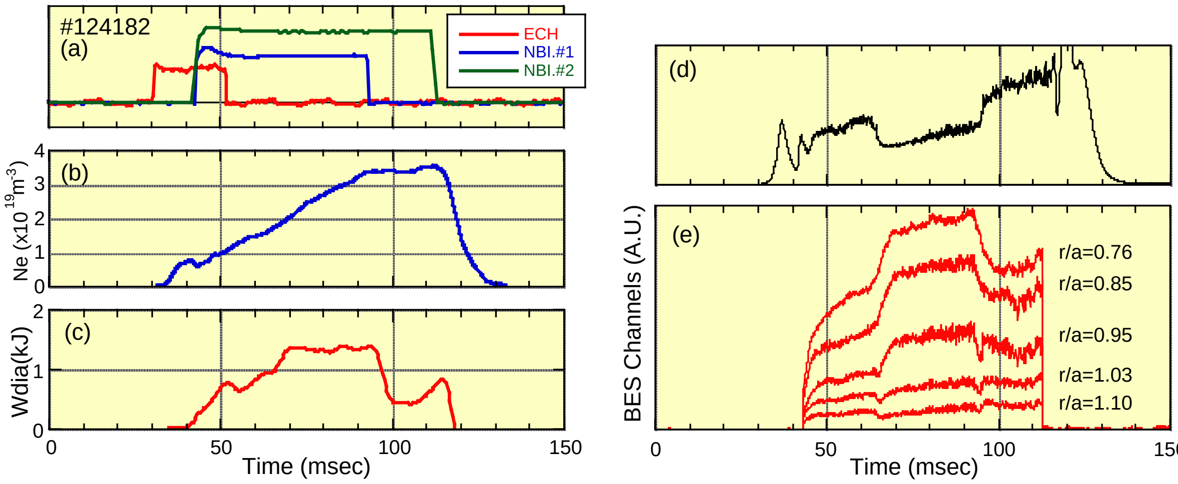

Fig. 3. Time traces of H-mode discharge. (a) ECH and NBI heating, (b) line-averaged density, (c) diamagnetic energy, (d) Hα emission signal and (e) BES signals at plasma edge.

Typical time traces of global parameters of H-mode discharge are shown in Fig. 3 for the 0.9 T magnetic field. An initial plasma is created by ECH and heated by two NBIs (both in the arrangement of co-injection). The plasma density is increased with the gas puffing, which initiates the H-mode transition at 64 msec. The delay time of the transition after the start of NBI heating depends on the magnetic configuration (the magnetic axis position and the rotational transform at the edge). Hα emission detector shows a sudden drop, which is very similar to tokamak H-mode. The plasma energy increases and the radiation from the bulk plasma also starts to increase at the transition. When the heating power is decreased by stopping NBI.#1, back transition takes place. Figure 3(e) shows the beam emission spectroscopy (BES) measurements for the local density information at the plasma edge [7]. Five channel signals in a range of normalized radii (r/a)= 0.76 to 1.10 clearly show the dynamic behavior of the local density pedestal formation in the edge region: the local density inside the barrier increases after the transition, and the density outside the barrier drops once just after the transition, but quickly recovers with the formation of the pedestal structure.

The dependence of the heating power threshold for ETB formation on plasma parameters is similar to tokamaks [8]. It increases with plasma density ($\propto Ne^{0.6}$) and magnetic field ($\propto B_t$). A unique feature is the dependence on the magnetic configuration. H-mode discharge is obtained for the limited range of magnetic configurations. Within this range, when the magnetic axis is shifted inward, the power threshold is increased. The absolute values of the power threshold for outward shifted configurations are the same as tokamak divertor discharges although CHS plasmas are in the limiter configuration.

3.2. Observation of Turbulence Suppression with ETB Formation

For any type of toroidal confinement, it is common understanding that the transport is dominated by the plasma turbulence related phenomena. From this aspect, it is expected that the fluctuation level in the plasma edge region should be reduced with the ETB formation. Four methods of fluctuation measurement were successful to confirm this expectation; wave scattering measurements using HCN laser and the laser imaging method using YAG laser, and local fluctuation measurements using BES and probes.

3.2.1. Fluctuation Measurements using Laser Diagnostics

Figure 4 shows the time variation of the density fluctuation spectrum obtained from the HCN laser scattering measurement (λ = 337 μm) [9]. Laser beam (width is 30 mm) passes through the plasma edge region ((r/a) = 0.9) and the scattered beam with 1.9 degree shift is detected, which corresponds to the wave number in the radial direction k_r = 5.4 cm^{-1}. Poloidal wave number is not detected due to the geometry of laser path in the plasma. Bottom figure shows the frequency spectrum; positive frequency corresponds to the wave propagating inward in the radius and negative one for the outward propagation. The turbulence develops after the NBI starts and sharply decreases at the L to H transition at 53 msec. During H phase, low frequency turbulence gradually increases as the the density increases.

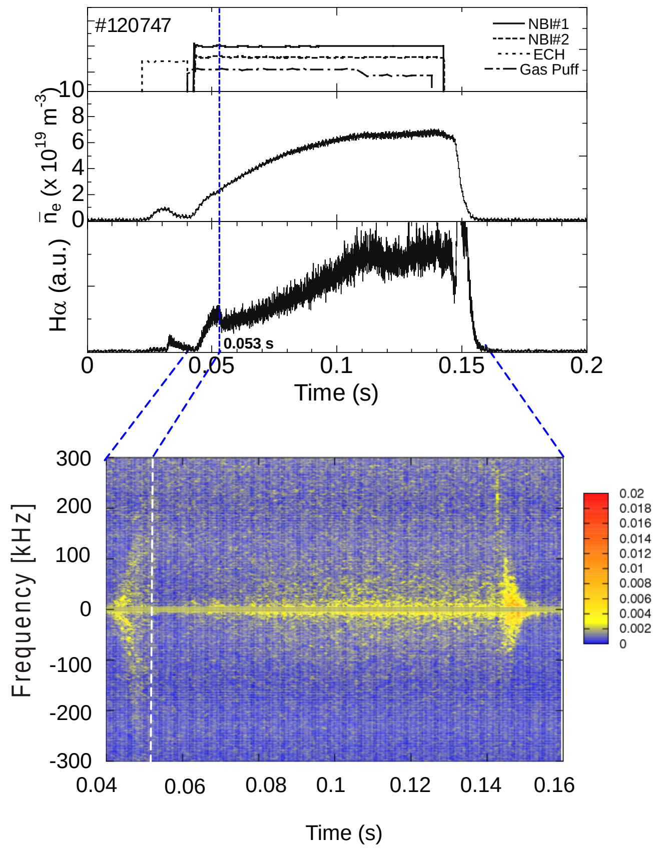

Fig. 4. Time variation of density fluctuation spectrum measured by HCN laser scattering for H-mode transition.

Another fluctuation measurement with a laser technique is the imaging method using a YAG laser (λ = 1.064 μm). YAG laser beam passes through the plasma column integrating fluctuations along the pass with the k vector perpendicular to the laser beam. So the fluctuations with the poloidal wave number are detected. The time variation of the fluctuation spectrum in the range of several 10 kHz shows a quick decrease of the fluctuation power at the L to H transition.

3.2.2. Fluctuation Measurements with Beam Emission Spectroscopy

The beam emission spectroscopy (BES) in CHS [7] measures Hα emission of high-energy hydrogen beam excited by bulk plasma electrons. NBI for plasma heating is used for the beam source. Eight channel detectors measure the local Hα emission (in the plasma edge region), which is proportional to the local electron density and its fluctuation (f < 100 kHz). Figure 5 shows the time variation of the root-mean-square value of the density fluctuation at four different minor radii in a H-mode discharge. The fluctuation decreases significantly at the normalized minor radius of (r/a) = 0.95, which corresponds to the position of the enhanced density gradient with H-mode transition. In the frequency spectrum, the suppression of the fluctuations is large for 20 to 60 kHz and is negligible for higher frequencies. The figure shows that the reduction of fluctuation level (0 to 60 kHz) at (r/a) = 0.95 starts several msec before the transition. The start timings of fluctuation suppression are different for different frequency range (lower frequency starts earlier). On the other hand, the fluctuation level at (r/a) = 1.1 drops just at the transition possibly because it is caused by the change of density profile at the edge.

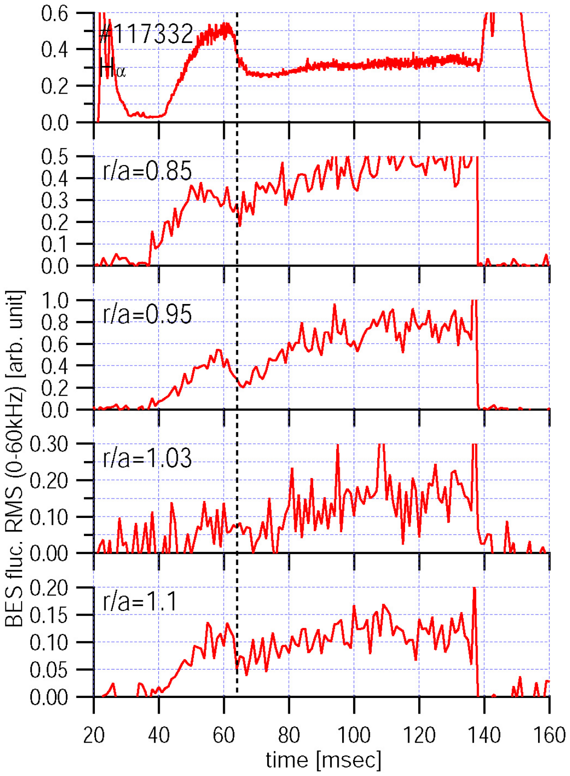

Fig. 5. Local density fluctuation measurement by BES for the edge plasma of H-mode discharge.

3.3. Measurement of Plasma Flow at H-mode Transition

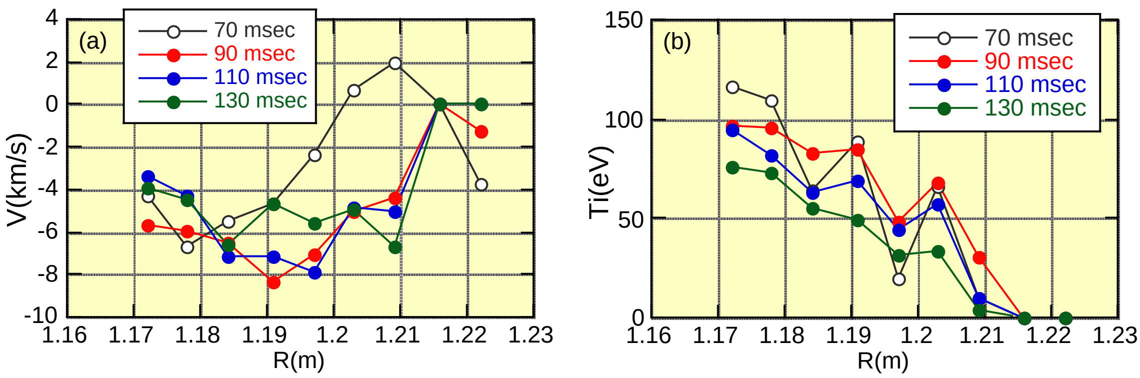

Fig.6. (a) poloidal flow velocity and (b) temperature measurement using carbon VI charge-exchange-exited line.

In tokamak H-mode, it has been understood that the electric field plays the most important role for creating the transport barrier at the edge. It was also confirmed in H-mode discharges of Wendelstein 7-AS experiment [10]. The charge exchange spectroscopic measurement in CHS also confirms the creation of the electric field at the H-mode transition. Figure 6 shows the radial profile of the poloidal velocity and temperature of fully ionized carbon ions (C^{6+}) measured with the line emission in the charge exchange process. Velocity is plotted in the ion diamagnetic direction. After H-mode transition at 80 msec, large velocity in the electron diamagnetic direction appears, a dominant term of which is E × B drift because the diamagnetic flow is small (E_r ~ 10 kV/m). This E × B flow gives the poloidal Mach number larger than unity, which is one of the conditions for the transition model of H-mode in tokamak.

Because this system has a 20 msec time window for each measuring point, discussion on the fast dynamics is not possible. The last closed magnetic surface from the equilibrium calculation is located about R = 1.21 m and the region of large poloidal velocity change at the transition is outside of (r/a) = 0.95.

4. H-mode Discharge in High Density with Reheat Mode

Because of the parameter dependence of the power threshold for H-mode transition described in section 3.1, the operation of H-mode discharge is relatively difficult for high density and high magnetic field condition. Nevertheless, by using the outward shifted configuration and the optimized NBI operation, it was successful to make H-mode discharges for high-density plasmas ($1 \times 10^{20} m^{-3}$) with high magnetic field.

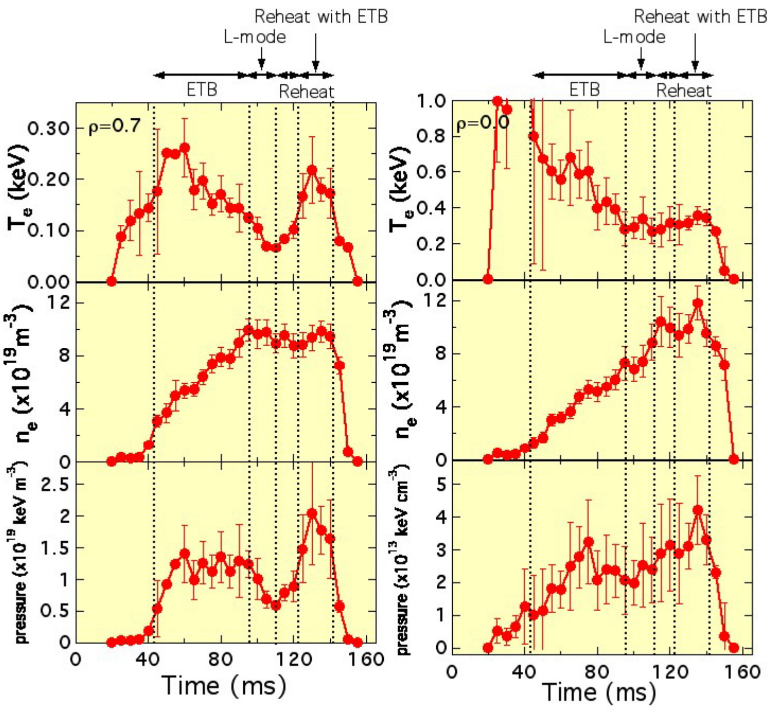

Fig. 7. Time behavior of local electron density and temperature measured by YAG Thomson for edge and central region.

Figure 7 shows time behaviors of electron density, temperature and pressure measured by YAG Thomson for plasma center and edge regions. At 43 msec, first H-mode transition appears with both edge density and temperature increase. Since the plasma density is increasing with gas puffing during H-mode, the temperature gradually decreases keeping the pressure almost constant. A back transition appears at 95 msec, because the power threshold condition is lost due to higher density. After back transition, the gas puffing is stopped introducing the reheat mode [11], which increases the edge temperature. Because the density comes down below the threshold condition, the second H-mode transition takes place finally producing the high edge temperature and pressure.

5. Conclusion

For ITB discharges, it was confirmed that the location of the transport barrier for the ion temperature is different from the one for the electron temperature. The reduction of the turbulent particle flux was measured by HIBP for discharges with ITB formation. For ETB physics, turbulence in the plasma edge region was measured by four different diagnostics and it was confirmed that measured fluctuations were suppressed with the ETB formation. The negative electric field of 10 kV/m at the edge plasma was measured with TVCXS during H-mode phase. New H-mode regime for high-density plasma ($1 \times 10^{20} m^{-3}$) was developed with reheat mode operation. This research was carried out under the NIFS budget code NIFS05ULPD601.

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