EX8-5Ra

Edge and Internal Transport Barrier Formations in CHS

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Abstract. Edge transport barrier (ETB) formation was observed in CHS. Sharp decrease of Hα emission indicates the quick transition of edge particle transport. Increase of the density gradient at the edge was measured by various profile diagnostics and the improvement of the global energy confinement was confirmed based on the stellarator confinement scaling. The heating power threshold exists. The transition and back transition is controlled by the heating power. The local density measurement by the beam emission spectroscopy shows intermittent burst of the low frequency fluctuations during the ETB formation phase. The ETB formation together with the electron temperature increase (electron ITB) in the core region were observed for the NBI discharges without ECH.

1. Introduction

The formation of transport barriers is an important research topic in the plasma confinement study for fusion research. Various types of transport barriers have been found in tokamaks and stellarators and physical mechanism of their formation has been studied intensively. In the Compact Helical System (CHS), which is a low-aspect-ratio middle size stellarator (R=1 m, a = 0.2 m, toroidal period number N=8), the H-mode discharge had been found in 1993 [1] which was the first finding in stellarators, simultaneously with the Wendelstein 7AS experiment [2]. This operation needed the control of the rotational transform at the plasma edge using an ohmic current created by the special operation of the poloidal coil current ramping. As well as the edge transport barrier (ETB) formation in the H-mode, the internal transport barrier (ITB) was found in CHS [3], also for the first time in the stellarator research. In the research of ITB, clear increase of the electron temperature and the potential at the central region of the plasma were measured for ECH plasmas. Now the ITB formation in stellarator has become popular for various devices. In addition to the electron ITB, new type of ITB was reported in the last FEC meeting [4] where the transport barriers were formed for both electrons and ions in the plasma with ECH and NBI heating. This type of ITB is unique for CHS experiment, which has not been observed in other stellarators yet.

In this conference, we report a new type of ETB formation (H-mode) in CHS experiment [5, 6]. This type of ETB discharges does not need ohmic current control. Sufficient level of NBI heating power is necessary for the transition which was not available in the previous H-mode study (threshold power for the transition clearly exists). With a large drop of the Hα emission, the edge density starts to increase due to the formation of the transport barrier for the particle flow. Since these ETB transition appears during the NBI phase without ECH, the electron temperature profile does not change much for most cases. However special discharges were found where the electron temperature increases together with density. The best case gives two times increase of electron temperature with the profile indicating the formation of the electron ITB without ECH. In this paper, characteristics of a new type of ETB will be described from various points of view and electron profile measurements for the combined ETB and ITB formation will be given.

2. Global Parameter Changes with ETB Formation

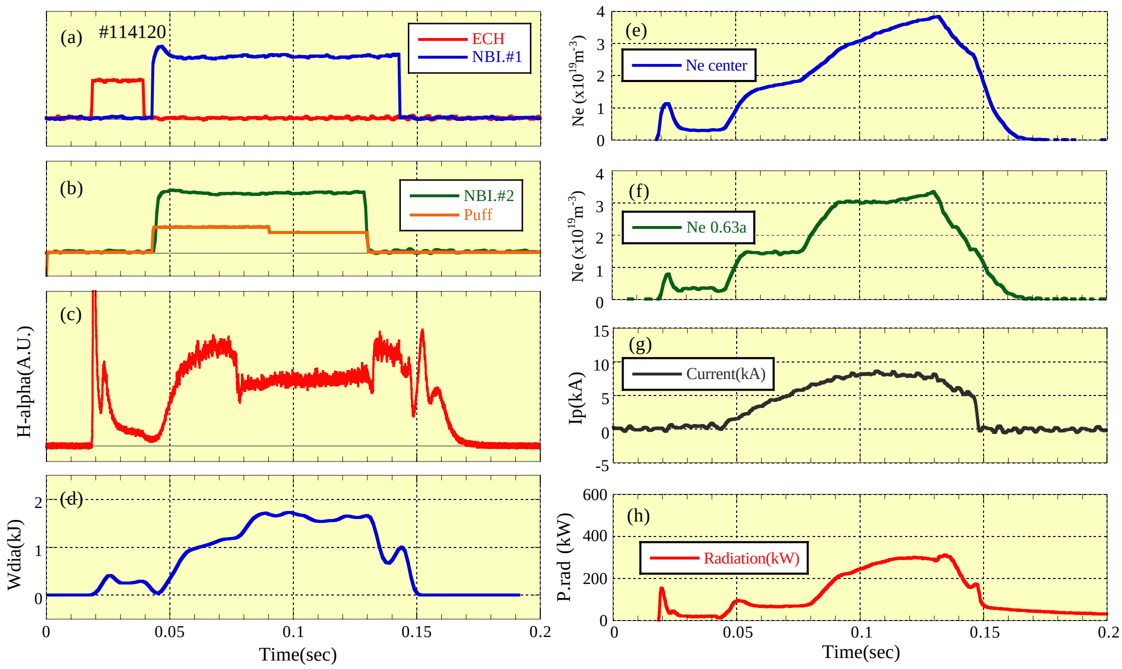

FIG. 1 Time traces of basic plasma parameters for NBI discharges with ETB formation. (a) and (b): ECH, NBI and gas puffing, (c) Hα emission, (d) diamagnetic energy, (e) line averaged electron density for central chord, (f) the same for edge chord, (g) plasma current and (h) total radiation power.

Figure 1 shows time traces of plasma global parameters showing the transition to the ETB formation and the back transition. The experimental condition of those discharges is as follows. The plasma volume is about 0.7 m^3 and its surface area is about 7.5 m^2. The magnetic field strength is 0.95 T at the magnetic axis. The profile of the rotational transform has a strong stellarator type shear at the plasma edge. It is 0.3 (=1/q) at the magnetic axis and slightly higher than 1 at the edge. The characteristics of magnetic surface parameters (rotational transform and magnetic well) is sensitive to the major position of the plasma and its (toroidally averaged) ellipticity. The cross section of CHS plasma is an ellipse (ellipticity is about 2) which rotates along the torus. The ellipticity we control by the axisymmetric poloidal field is the toroidally averaged one. The configuration shown in Fig. 1 has the magnetic axis position R_{ax} = 92.1 cm and the ellipticity κ = 1.22.

Two neutral beams are injected into the low density hydrogen plasma created by the ECH heating (53 GHz, 200 kW). Both beams are installed tangentially to the torus making co-injection. Beam energy for two NBIs are 40 and 30 keV, respectively, and the maximum port-through injection power is about 800 kW for each. Such an arrangement is essential for supplying sufficient heating power for the ETB transition because the counter-injection gives large direct loss of beam ions. As shown in Fig.1, the plasma is sustained by NBI and density increases with gas puffing. After 35 msec from the starting of NBI, a spontaneous transition appears in the plasma edge region which is clearly shown by the sharp drop of Hα emission signal. The estimated NBI deposition power is about 0.6 MW before the transition. The delay time between the start of NBI heating and the transition largely depends on the magnetic configuration and the heating power. Figure 1 shows two chord signals of HCN interferometer at the center (e) and the normalized minor radius of 0.63 (f). These data show that the density profile becomes slightly peaked during the NBI heating phase with the edge density staying almost constant. After the transition at 78 msec, the edge density starts to increase making a flatter profile and the diamagnetic plasma energy increases as well (volume averaged beta is 0.6 % after the transition). The total radiation loss from the plasma also starts to increase. When the NBI.#2 is turned off and the heating power is decreased, the back transition appears. The plasma current is a combination of the bootstrap current and the beam driven current. The current level of 8 kA in this shot gives the increase of the edge rotational transform of 0.035 which is not larger than the ambiguity of the edge value given from the equilibrium calculation.

3. Local Profile Measurements

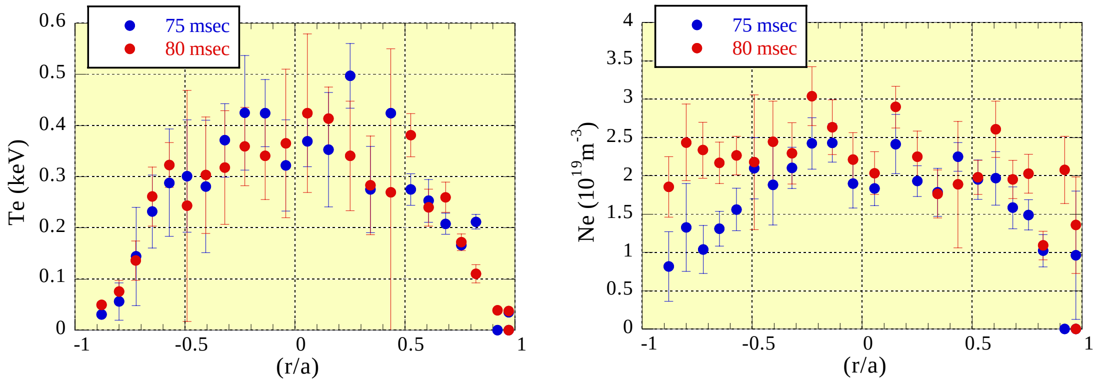

FIG. 2 YAG Thomson scattering measurements for electron temperature (left) and density (right). Blue point profile is before the transition and red one is after the transition.

The change of density profile at the transition was clearly measured by the YAG Thomson scattering system in CHS which gives full profiles of electron temperature and density every 5 msec. Figure 2 shows measured profiles of the same discharge shown in Fig.1 at 75 msec (just before the transition) and 80 msec (after the transition). The edge density increases after the transition making the large density gradient at the plasma boundary. However the temperature profiles does not change much for this discharge.

Edge density profile measurement was made also by the lithium beam probe system [7]. Accelerated neutral lithium beam (15 keV) was injected into the plasma edge region and the Li I resonance line emission excited by the electrons was measured along the beam. This diagnostic gives the electron density profiles for larger area at the boundary where the electron temperature is not high enough for the standard Thomson scattering system which is designed for taking plasma core temperature profile. Figure 3 shows the variation of the edge density

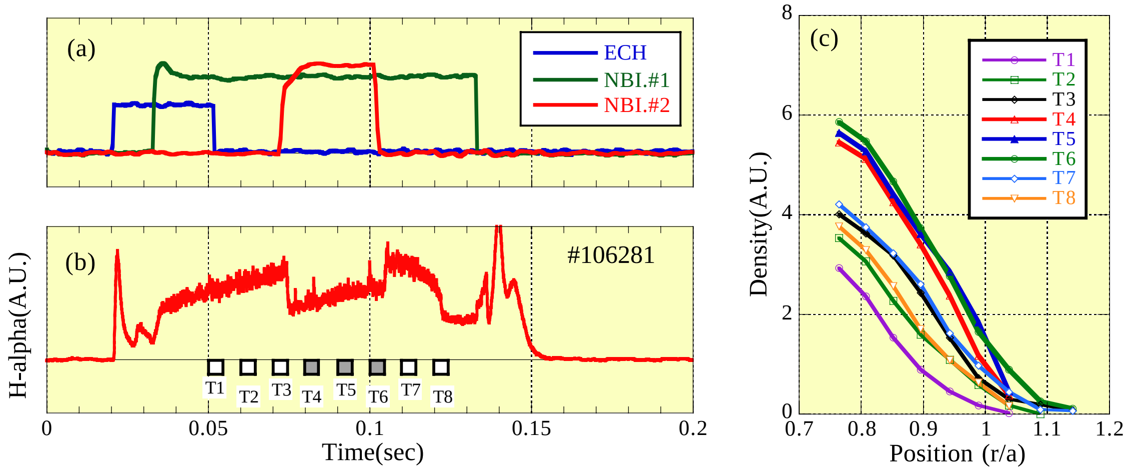

FIG. 3 Density profiles measured by lithium beam probe. Data averaging periods are shown in (b). Position in (c) is plotted as a function of averaged minor radius.

profiles for whole period of the discharge. In this discharge, the second beam NBI.#2 is injected for shorter period (from 72 msec to 102 msec) than NBI.#1 in order to confirm the transition to ETB and the back transition controlled by the heating power. The increase of the edge density is observed for time periods from T4 to T6 where the ETB is formed.

Another local density measurement in CHS is the beam emission spectroscopy (BES) which measures Hα emission of high energy hydrogen beam excited by electrons [8]. NBI.#2 is used for the beam source for BES measurement. An eight channel array of visible detectors is installed for getting the spatial density profile near plasma edge region. Since this system has the high frequency response (< 100 kHz), local fluctuation measurement is also made which is discussed later. Figure 4 shows the time variation of three BES channels for the discharge with ETB formation. When the ETB is formed at 70 msec, BES signals looking at inside of the last closed magnetic surface (LCMS) rapidly increase and the BES signal for the outside of LCMS drops indicating the suppression of the outward particle flow by the transport barrier. After forming the large density gradient, the edge density increases and finally stays constant. In the Hα emission signal, a pre-phase of the drop is recognized where the BES signal inside the plasma starts to increase (Fig.

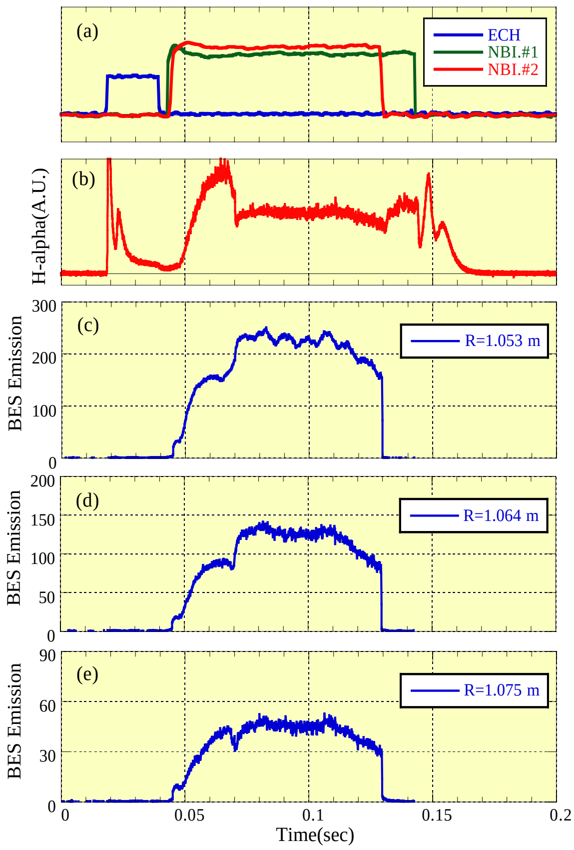

FIG. 4 BES measurements of local electron density. Calculated LCMS is between measurement position of (d) and (e)

4(c)) while others do not change at all.

4. Dependence of ETB Formation on Heating Power

Heating power threshold is clear for the ETB formation in CHS. When the heating power is decreased, the time delay between the starting of NBI heating and the spontaneous transition becomes larger. If the heating power is close to the power threshold, sequence of short spikes of Hα emission signal appears indicating the dithering between the H and L state [5]. When the heating power is decreased further, the spontaneous switching between two states appears and finally no transition occurs for the heating power below the threshold.

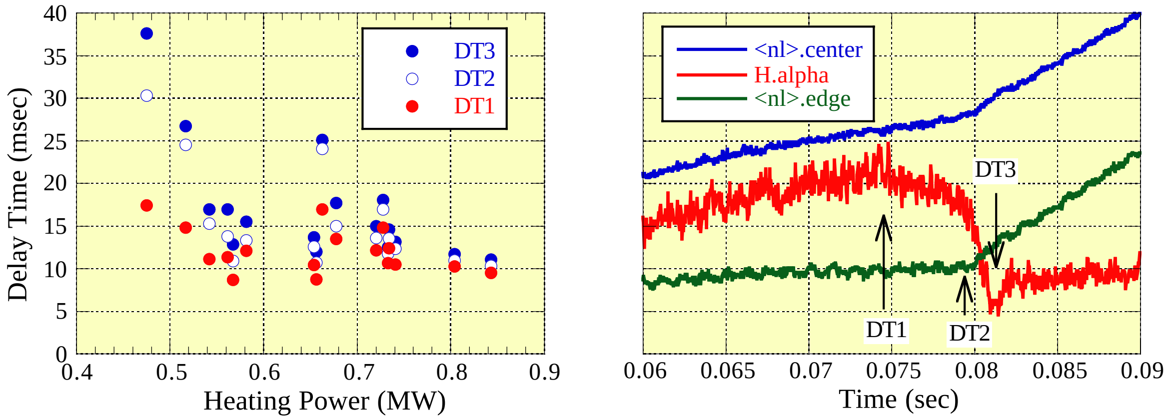

FIG. 5 Time delay of Hα signal drop after NBI start as a function of heating power. Three characteristic instants are shown in right figure.

Figure 5 shows the dependence of time delay of the transition from the starting of NBI as a function of deposition power. The magnetic configuration with R_{ax} = 92.1 cm and κ = 1.11 was used. In this configuration, the delay time of the transition from the start of NBI heating is generally much shorter than the case in Fig. 1. Three timings are taken corresponding to the various phase of Hα emission change shown in the right figure. DT1 is the beginning of whole transition phenomena. Hα signal starts to decrease slowly in the pre-phase between DT1 and DT2. The quick decrease of the signal appears between DT2 and DT3. Although we do not have complete understanding of these phases, local particle dynamics might be related to these phases of Hα signal (e.g., BES signal in Fig. 4(c) shows slow increase in the pre-phase). When the heating power is decreased down to the power threshold, the delay of the quick drop phase is increased while the starting of the pre-phase does not change so much. Even though the timing of the quick drop is delayed, the speed of signal drop does not change much. But finally main drop of the signal becomes slow at the power threshold.

The heating power threshold is about 0.5 MW for the density of 2 x 10^{19} m^{-3}. For the lower density plasma (1.5 x 10^{19} m^{-3}), the power threshold is decreased roughly proportionally. On the other hand, the gas puffing is necessary condition for making the ETB formation. ETB does not appear for very low density plasmas without gas puffing. The power threshold obtained in the CHS experiment can be compared with the tokamak H-mode threshold scaling because it consists only of the density, magnetic field and device size parameters [9]. CHS power threshold is roughly two times larger.

5. Confinement Improvement

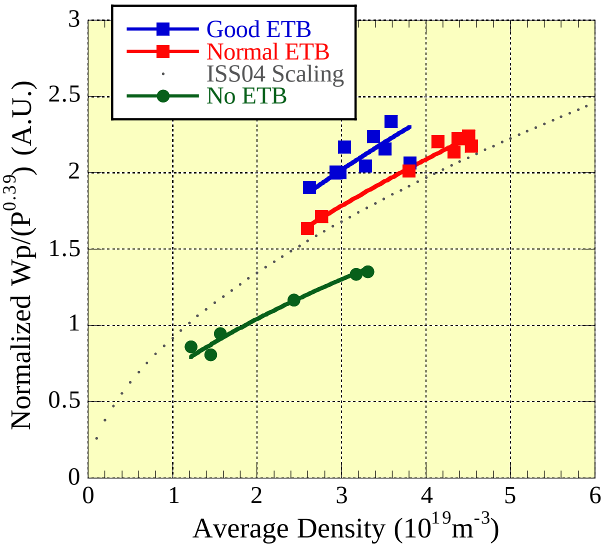

FIG. 6 Plasma energy normalized by the scaling factor for P as a function of averaged density.

Due to the formation of ETB, the plasma energy increases by about 40% as is shown in Fig. 1. The analysis of discharges with and without ETB based on the global energy confinement scaling is shown in Fig. 6. Data are taken from the density scanning experiment (with gas puffing control) where the NBI port through power was kept almost constant (1.3 to 1.4 MW). In this experiment, the magnetic configuration with Rax = 92.1 cm and κ = 1.11 was used. Data for 'Good ETB' were obtained with the wall conditioning of strong titanium gettering. Maximum diamagnetic energy during the discharge is taken for Wp. If the plasma density does not reach the threshold level during the initial phase of discharge, ETB is not formed even though the density in the later phase rises up. The diamagnetic energy devided by the scaling factor for the NBI deposition power is plotted as a function of the averaged density. Confinement scaling from the new international cooperation for stellarators is used [10]. The black dotted line is from this scaling for the middle size heliotron type devices with CHS parameters. Three fitting curves are added according to the density scaling law with different coefficients. The formation of ETB makes confinement improvement above the scaling law. The intense wall conditioning improves additionally the confinement.

6. Fluctuation Measurement by BES

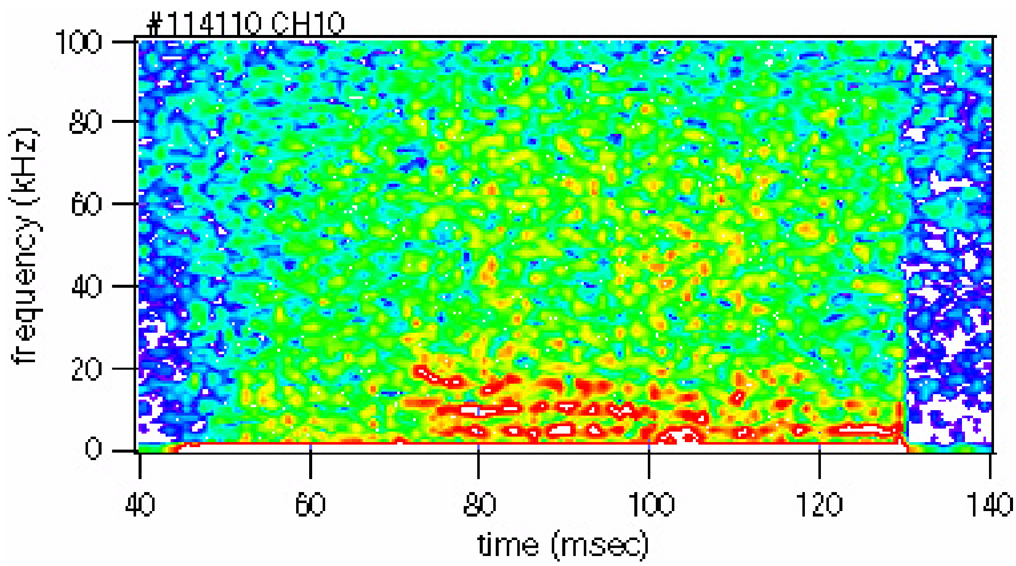

FIG. 7 Time variation of power spectrum in BES signal just inside LCMS. Red color corresponds to largest power. ETB is formed at about 70 msec.

High frequency components in the BES signal were analyzed in order to compare the fluctuation level in the L and H phase. During the H phase with ETB formation, low frequency fluctuations appear near the plasma boundary. Figure 7 shows the time variation of the spectrum profile of BES signal looking at just inside LCMS for the same discharge shown in Fig. 4. The fluctuation level is largest for this channel among all 8 channels observing across LCMS. Logarithmic value of power spectrum is shown by colors (red is highest). After the ETB formation at 70 msec, fluctuation level rises with the frequency of about 5 kHz and its harmonics. They appear intermittently with the period of a couple of msec. From the detailed analysis of initial time variation of those fluctuations and the density profile, it is confirmed that those fluctuation starts after the formation of a steep density gradient at the plasma edge. The physical mechanism of those fluctuations and its effect on the transport has not been understood. From BES edge density fluctuation measurements so far, we have not observed any evidence of the suppression of fluctuation level during ETB phase.

7. ETB with Temperature Increase in the Core Region

As was mentioned in section 3, for most discharges the electron temperature profile does not change much with the ETB formation. However we observe occasionally the increase of the electron temperature in the core region just after the ETB formation. This increase of the temperature cannot be understood by the increase of the heat deposition with the increased density because the increase of heating power is only proportional to the density at maximum. There must be the transport improvement or the transport barrier. Such an increase of the electron temperature appears only in a short time (10 to 20 msec) because of the rapid density increase with the ETB formation. Systematic study for the operational condition of those mode and the method of making the phenomena steady are necessary.

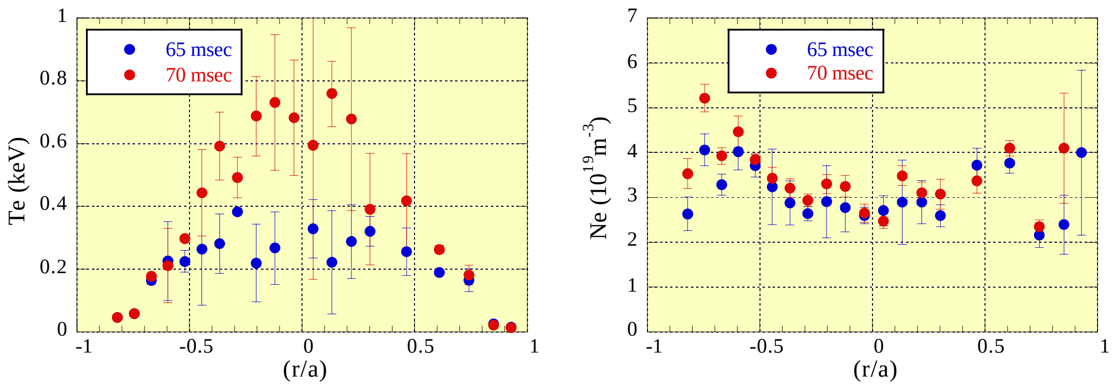

FIG. 8 Electron temperature and density profiles for ETB discharge with simultaneous ITB.

Figure 8 shows one example of electron density and temperature profiles of an ETB discharge with the raised electron temperature in the core. The profile shape of the electron temperature is very similar to the ITB discharge in CHS [4]. However in the previous ITB experiment, the electron temperature increase and the steep temperature gradient are made after the application of ECH. In this ETB discharge, the ECH for the target plasma production is turned off before the transition. More important difference is the plasma density. In the previous ITB experiment, there was a clear density threshold for the ITB formation at 0.4 x10^{19} m^{-3} (lower density operation is necessary). The mechanism for the creation of the electric field shear is considered to be given by the intersection of the positive and negative electric field region (electron root and ion root) created by the neoclassical non-ambipolar diffusion process in stellarators. With this reason, we called this type of ITB as neoclassical ITB (N-ITB). The ITB formation in the present experiments should have a different physical mechanism because the neoclassical electron root cannot be created for such a density and temperature region.

8. Discussion and Summary

Following to the series of ITB physics studies in stellarator initiated by CHS experiment in 1999, the NBI discharges with ETB formation (H-mode) has been extensively studied. Those experiments became possible because of the improved heating efficiency of two NBIs by arranging them in co-injection together instead of balanced injection. Clear drop of Hα emission signal was observed and the quick increase of the edge density was measured by YAG Thomson and BES. The experiments confirming the existence of heating power threshold clearly showed that the transition is controlled by the amount of heat flow through the plasma boundary. The time delay of the transition from the start of NBI depends on the heating power. It also depends very sensitively to the magnetic configuration (more important is the edge rotational transport value). The physical mechanism to determine the instant of transition is an important topic for the future study. The electron temperature does not increase much for most discharges. However large increase of the electron temperature was observed for the limited number of discharges where the temperature gradient appeared for the density of 2 x 10^{19} m^{-3} which is well above the density threshold for the previous ITB experiments in CHS. Further study of this type of confinement improvement is essential for fusion research for stellarators.

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