Characteristics of H-mode-like discharges in LHD
under the presence of 1/1 rational surface at ergodic layer

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1. Introduction

The plasma behavior is affected by the rational surface existing at the plasma boundary. H-mode-like discharge is one of the typical examples. In W7-AS [1] the H-mode-like discharge was obtained only when the major rational surface was produced at the plasma boundary in net-current-free ECH plasmas. In CHS [2,3] a similar discharge was also obtained by additionally introduced ohmic current in NBI plasmas, which changed an edge rotational transform, $\iota(a)/2\pi$. Recently, the H-mode-like discharges have been successively obtained in CHS NBI plasmas [4] and Heliotron-J ECH plasmas [5] by varying the $\iota/2\pi(a)$ values without externally induced plasma current.

In LHD, on the other hand, an H-mode-like discharge appeared in high-β plasmas ($\beta\sim2\%$) with a low magnetic field ($B_t<0.75T$) at $R_{ax}=3.60m$ ($\iota/2\pi(a)=1.56$) [6]. The growth of m/n=2/3 modes appeared at the edge barrier region with the saturation of plasma performance. Recently, an H-mode-like discharge has been newly obtained in a full B_t field ($B_t=2.5T$) by shifting the R_{ax} outwardly ($R_{ax}=4.00m$) [7]. In this paper characteristics of the H-mode-like discharges are briefly reported.

2. Edge rotational transform and connection length of magnetic field

Edge rotational transform at $\rho=1$ and averaged plasma minor radius in LHD are plotted in Fig.1 (a) and (b) as a function of magnetic axis position, R_{ax}. The edge rotational transform ranges in $0.7< \iota/2\pi(a) <1.6$. The 1/1 surface is located at $\rho=0.88$ in a standard vacuum configuration of $R_{ax}=3.60m$ and located at $\rho=1.0$ near $R_{ax}=3.90m$. The plasma size becomes small, but the thickness of ergidic layer surrounding the core plasma becomes large when the R_{ax} is shifted outwardly.

Figure 2 shows edge radial profiles of magnetic field connection length, L_c, and $\iota/2\pi$ at a horizontally elongated position in $R_{ax}=3.90$, 4.00 and 4.10m. It is seen that the thickness of the ergodic layer becomes
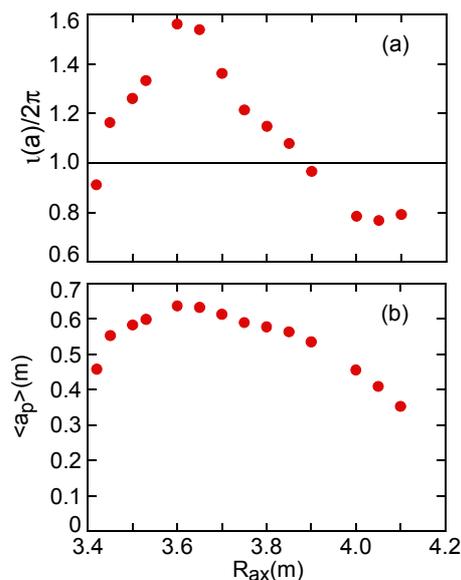

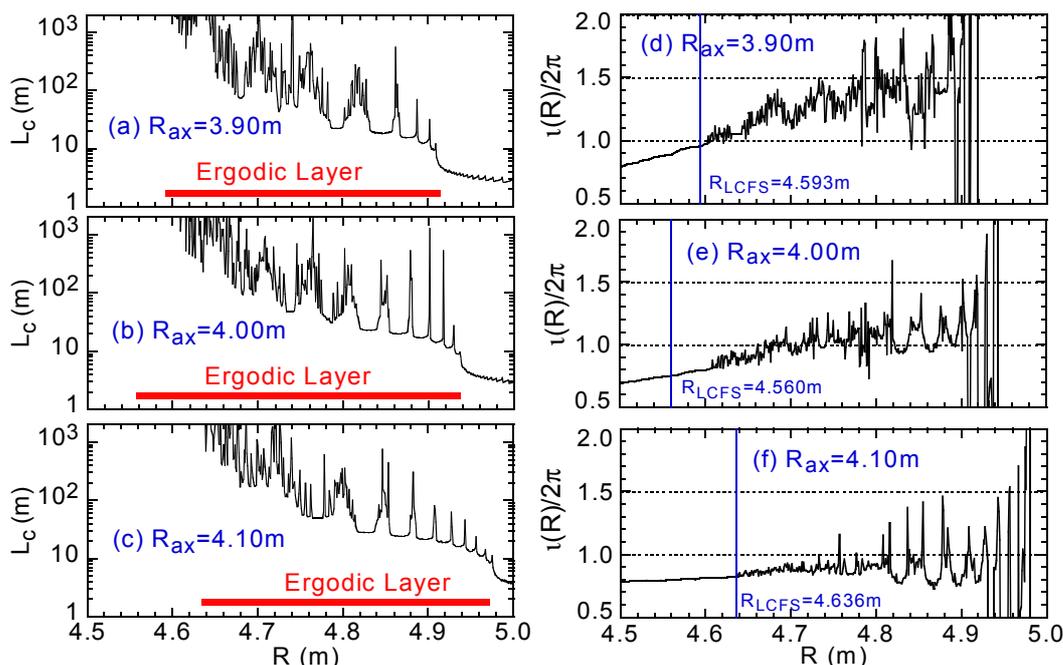Fig.1 Edge rotational transform (a) and averaged plasma radius (b) as a function of magnetic axis, R_{ax}.

Fig.2 Edge radial profiles of magnetic field connection length ((a) R_{ax}=3.90m, (b) 4.00m, (c) 4.10m) and rotational transform ((d) R_{ax}=3.90m, (e) 4.00m, (f) 4.10m). The positions of LCFS are indicated with vertical solid lines.

large at the X-point and closes to 40cm. The X-point exists at the outside of LCFS in the figure. Real outside boundary of the plasmas is determined by the competition between heat input and heat loss inside the ergodic layer, although it is, of course, a strong function of the connection length. The positions of the 1/1 surface in R_{ax}=3.90 and 4.00m are located near the LCFS and outside of ergodic layer, respectively. No 1/1 surface exists substantially in R_{ax}=4.10m. Thus, it is understood that the pressure gradient of the 1/1 surface is very sensitive to the heat flux in the case of R_{ax}=4.00m.

In LHD, at present, the LCFS positions indicated in the figure are defined by the outermost flux surface on which the deviation of the magnetic field line is less than 4mm while it travels 100 turns along the torus [8]. Then, the position of the LCFS is affected considerably by the presence of small islands near LCFS, as did appear in the case of R_{ax}=4.00m. The distance between the 1/1 rational surface and the LCFS defined in this manner is about 12cm at the horizontally elongated plasma position in the case of R_{ax}=4.00m.

3. H-mode-like discharges

Experimental trials have been made regarding such three configurations. As a result, the H-mode-like transition was appeared in R_{ax}=4.00m by changing the NBI input power while maintaining a relatively high density. No transition was obtained in R_{ax}=3.90 and 4.10m. This result strongly suggests the importance of the 1/1 surface at the plasma edge for the H-mode-like discharge.

A typical waveform is shown in Fig.3. One of three NBIs is turned off at t=1.25s. After turning off the beam line, the Hα emission quickly drops and the density gradually rises, showing a clear turning point. ELM-like bursts appear in the Hα signal. Similar bursts are

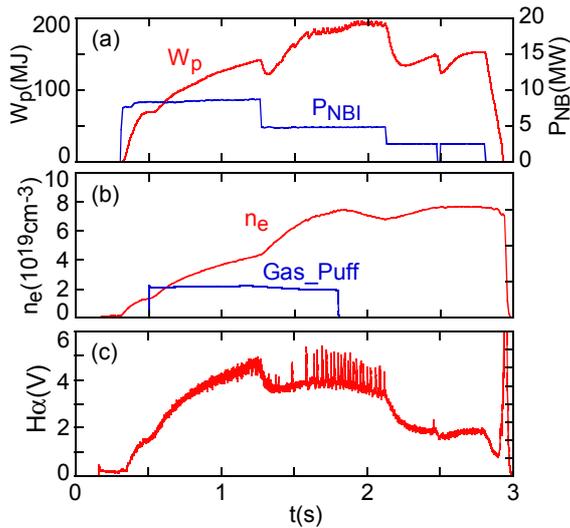Fig.3 H-mode-like discharge after P_{NBI} decrease; (a) W_p, (b) n_e (c) $H\alpha$.
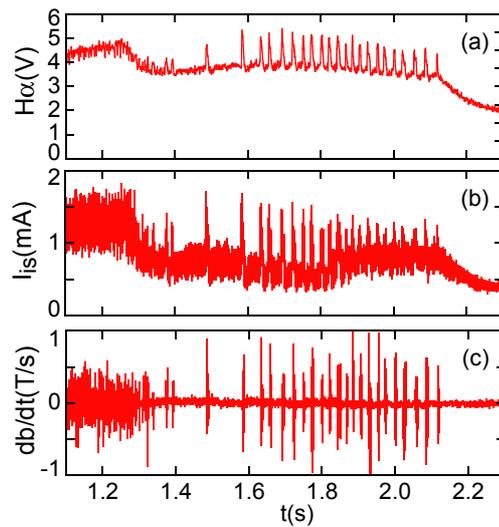
Fig.4 Enlarged signals of Fig.3; (a) $H\alpha$, (b) I_{is}, (c) db/dt.

also observed in an electrostatic probe on the divertor plate (I_{is}) and a magnetic probe (db/dt). They are also traced in the expanded time scale in Fig.4. Reduction of the magnetic fluctuation is seen after the H-mode-like transition.

This H-mode-like feature, however, disappears after turning off the second NBI at t=2.1s. It strongly suggests that a relatively narrow power window exists for appearance of the H-mode-like phase. In order to confirm the existence of power window the P_{NBI} was increased from one beam to two beams, as shown in Fig.5. The H-mode-like phase was obtained only in the time interval of the P_{NBI} increase during t=1.8-2.8s.

In addition, the H-mode-like discharges cannot be obtained in low- and high-density ranges, appearing only in a density range of $4-8\times10^{13}\text{cm}^{-3}$. This fact strongly suggests that

Fig.5 H-mode-like discharge after P_{NBI} increase.

this phenomenon is sensitive to plasma conditions around $\iota/2\pi(a)=1$ surface. The pressure gradient at the position of 1/1 surface could be a driving force for appearance of the $H\alpha$ bursts.

The edge density behaviors were analyzed from signals of multichannel interferometer, which measures vertical chord-integrated densities (n_eL) at vertically elongated plasma cross-section. Temporal behaviors of two chord-integrated densities from edge region at inboard side are traced in Fig.6 (b) and (c) with the connection length in Fig.6 (a). The ergodic layer becomes thick at the inboard side in such outwardly shifted configuration of $R_{ax}=4.00$m. The position of LCFS is R=3.529m at the inboard side. Then, both signals in Fig.6 (b) and (c) show the density from the ergodic layer. One of the densities (R=3.489m) in Fig.6 (c) is close
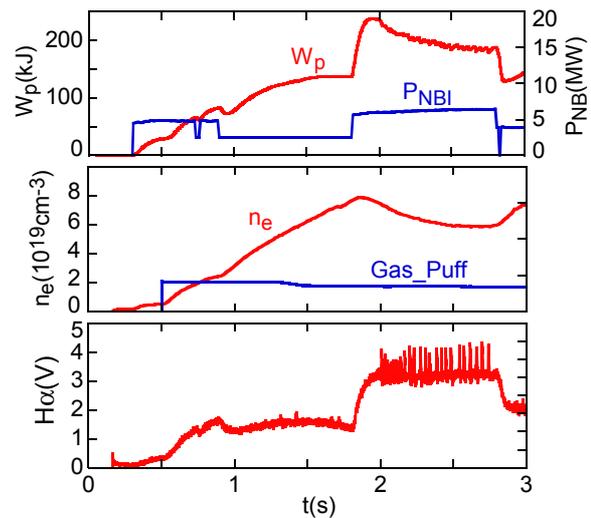
to the LCFS. Relatively high density exists even in R=3.399m where the L_c is roughly 100m.

The density bursts become remarkable in the inboard side as seen in Fig.6 (b) and can be well correlated with the Hα bursts. The density from R=3.489m in Fig.6 (c), however, indicates an inverse temporal behavior. A density collapse toward the plasma boundary from the inside is seen. It is calculated that the 1/1 surface in this position exists near R=3.46m located between two interferometer chords of R=3.399 and 3.489m. The position of the 1/1 surface possibly corresponds to the inversion radius of the density collapse. This density collapse appeared inside the ergodic layer suggests that some part of the ergodic layer having a relatively long L_c behaves like a core plasma with well-defined magnetic surface. In other

Fig.6 L_c at vertical-inside of R_{ax}=4.00m (a) and enlarged n_eL of Fig.3 (b), (c). Two arrows indicate positions of measured n_eL.

words, the perpendicular diffusion becomes important in such a region. Then, the presence of the 1/1 surface at the ergodic layer can play an important role in terms of the confinement improvement, e.g, formation of a sharp boundary.
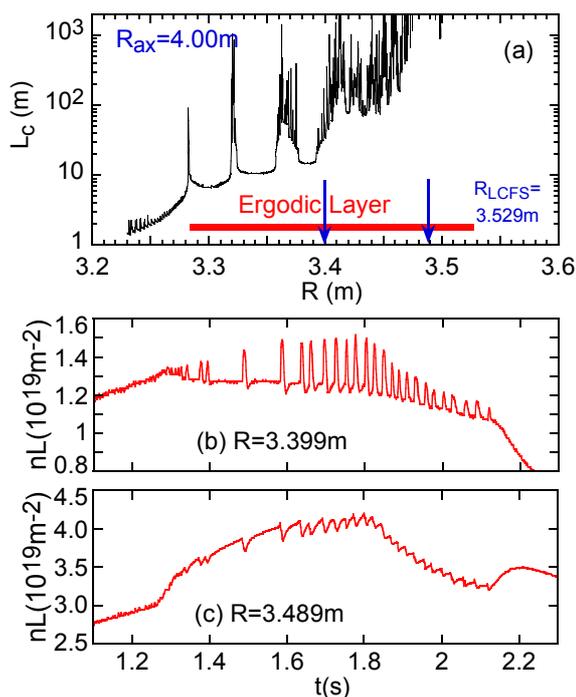
4. Concluding remarks

Since the tangency radius of the present NBI is R=3.70-3.75m, the energy confinement in such an outwardly shifted configuration is always much smaller than in ISS-95 scaling due to less central heat deposition. The energy confinement times obtained in the discharge shown in Fig.3 are 17ms (τ_{E_ISS95}=36ms) and 41ms (τ_{E_ISS95}=65ms) at t=1.2 and 2.0s, respectively. A clear confinement improvement has not been observed at present. However, the H-mode-like discharges mentioned above, at least, provide us interesting data related to the edge physics. For this purpose edge plasma diagnostics becomes more important in LHD, because we have now no exact information on the density and temperature profiles in the ergodic layer.

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