Studies of HRS H-mode plasma in the JFT-2M tokamak

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Abstract. An attractive operational regime without any large ELMs, namely "High Recycling Steady" (HRS) H-mode, has been found on JFT-2M during Y2000 campaign after a boronization. Recent experiments have been concentrated on the studies of the access conditions for the HRS regime, in terms of the pedestal parameters. The HRS regime was more likely at higher edge density and lower edge temperature, which corresponds to the normalized electron collisionality of $\nu_e^* \geq 1$ at the edge pedestal. The effects of the plasma shape were also investigated. Then, we have newly extended the HRS operational regime toward higher energy confinement utilizing the capability of both high triangularity $\delta \geq 0.7$ and elongation $\kappa \geq 1.6$ operation under the double-null (DN) configuration. The energy confinement time enhancement factor (H_{89P}) in the HRS plasma under the DN configuration increased up to ~2 at around $n_e/n_{GW} \sim 0.4$, which was close to that of the standard ELMy H-mode regime having large ELMs under the single-null (SN) configuration ($\delta/\kappa \sim 0.4/1.4$). A series of parameter scan was also performed in the q_{95}-δ space under the limiter (LIM) configuration. The HRS H-mode was easily reproduced in the D-shaped plasmas, while the large ELMs appeared in the circular cross-sectional shape. These observations indicate an important role of plasma shaping to access the HRS regime as well as edge cpllisionality. A key feature of the HRS H-mode is a reduction of the transient heat load to the divertor target due to large ELMs. It was estimated to be about ~0.3 MW/m^2 in the typical HRS plasmas, which was significantly small in comparison with the transient heat load of ELMy H-mode discharge. The edge MHD activities in the frequency range of the order of 10-100 kHz were recognized to be important for an enhanced particle transport and steady H-mode edge condition in the absence of large ELMs.

1. Introduction

To establish an alternative scenario to the Type-I ELMy H-mode is a key area of research for current tokamaks, such as EDA regime on Alcator C-Mod [1], Type-II ELMs on ASDEX-Upgrade [2], QH-mode regime on DIII-D [3], Type-III ELMs in impurity seeded discharge on JET [4], Grassy ELMs on JT-60U [5]. These discharges show a strong reduction of the ELM activities, reducing transient heat loads on the divertor target. Better understanding of these operational scenarios is important to design future devices.

In the JFT-2M tokamak (major radius R=1.31 m, minor radius a≤0.35 m) [6], an attractive "High Recycling Steady" (HRS) H-mode operating regime without any large ELMs has been discovered after boronization [7-9]. The HRS H-mode plasma is characterized by a good energy confinement at a high density ($1.2 \leq H_{89P\ [10]} \leq 1.6$ at $0.4 \leq n_e/n_{GW} \leq 0.7$), low radiation loss power fraction ($P_{rad}^{main}/P_{in} \sim 0.2$, typically), and the disappearance of large ELMs. Here, n_e/n_{GW} is the electron density normalized to the Greenwald density [11]. Accompanying the HRS H-mode transition, coherent magnetic fluctuations are usually seen on magnetic probes at the vessel wall in the frequency range of the order of 10-100 kHz with significant variation. It is believed to be important for an enhanced particle transport seen in the HRS plasmas. These features seem to be similar to that observed in the small- and/or no-ELM regimes on other devices, although a detailed comparison of the characteristics of global behavior, edge fluctuations, and access conditions in terms of the dimensionless parameters, show distinct difference in their behavior.

At present, the HRS regime can be robustly reproduced with all combinations of co-, balanced-, and counter- neutral beam injection (NBI) and fueling from the boronized first wall (no external gas puffing). The HRS H-mode operation requires high density ($n_e/n_{GW} \geq 0.4$, typically) and/or neutrals (midplane neutral pressure $p_0 \geq 5$-10 mPa, typically) under a clean wall condition after boronization (within ≤500 shots, typically). The HRS H-mode has reproduced in single-null (SN) divertor configuration with both favorable and unfavorable directions of the grad-B drift in terms of the threshold power for H-mode transition. In order to investigate the possibility to extrapolate the HRS H-mode to future devices and to compare it to other small ELM regimes, the accessibilities to the HRS regime are quite important to understand.

This paper reports the results of the 2003-2004 experiments with a particular focus on the access conditions for the HRS regime in terms of the edge plasma parameters, including the pedestal pressure, collisionality, safety factor, and plasma shape. In addition, We have also investigated the heat load to the divertor plate by means of the Langmuir probes in SOL on the target plates in addition to the 2D measurement of the D_α emission utilizing the fast framing CCD camera.

2. Comparison between ELMy and HRS H-mode plasmas

2.1. Global behaviour

We performed following experiments with deuterium plasma heated by the hydrogen NBI. The plasma configuration for this study has standard shaping for JFT-2M with triangularity δ~0.5 and elongation κ~1.5 under the upper single-null configuration. In this experiment, the boronization was carried out with DC glow discharge in mixture gas of 1% $B(CH_3)_3$ (tri-methyl-boron, TMB) + 99% He.

Figure 1 shows a comparison among typical ELMy, Mixture, and HRS discharges activities at same I_p/B_T=0.25 MA/1.8 T (corresponding safety factor at the 95% flux surface q_{95} is ~3.5), under balanced-NBI heating with P_{NB}~1.4 MW. At the lower target density (#99937), a transition into the ELM-free H-mode occurs at t~650 ms, as seen by a drop in the D_α light. Then, the electron density (n_e) and stored energy (W_{MHD}) begin to rise at the same time until the onset of large ELMs at t~707 ms. At the higher target density (#99941), a transition into an HRS H-mode occurs after a brief ELM-free period at t~617 ms, which is indicated by a rise in the D_α intensity with small ELMs. In the following HRS phase, the density reaches a new plateau value without any large ELMs, keeping a low radiation loss power even at high density, typically $P_{rad}^{main}/P_{in} \leq 0.2$. There is also Mixture-type discharge (#99940) at intermediate target density between ELMy and HRS, whose amplitude of ELMs (I_{ELM}) and base level of the D_α signal ($I_{D\alpha}$) are of intermediate between these two conditions.

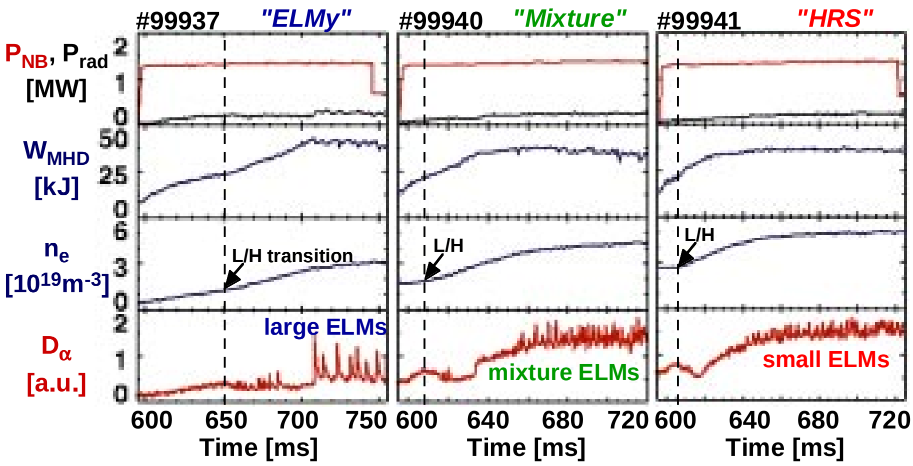

FIG. 1. Time evolutions of three H-mode discharges at I_P/B_T = 0.25 MA/1.8 T (q_{95} ~3.5).

2.2. Pedestal characteristics

It is considered that variations in the global behavior among these three H-mode discharges are related to the change in the pedestal parameters. As shown in Fig. 2 (a), ELMy discharges (e.g. #99937) are more likely at lower edge density $n_{e,edge}$ and higher edge temperature $T_{e,edge}$, while HRS discharges (e.g. #99941) occur at higher $n_{e,edge}$ and lower $T_{e,edge}$. The Mixture discharge (e.g. #99940) also occurs between the ELMy and HRS regimes in the edge n_e-T_e space. These results indicate that the ELMy/HRS operational boundary exists at a normalized electron collisionality of ν_e^*~1 in the plasma edge region near the pedestal top, which is defined as the ratio of collision frequency to the bounce frequency as $\nu_e^* \equiv 6.9\times10^{-18} q_{95} R n_e \ln\Lambda/(T_e^2\varepsilon^{3/2})$. Where R is major radius, n_e is electron density (measured by FIR interferometer from the chord passing through at r/a~0.85), $\ln\Lambda$ is Coulomb logarithm, T_e is electron temperature (measured by ECE radiometer at r/a~0.9), and ε is inverse aspect ratio.

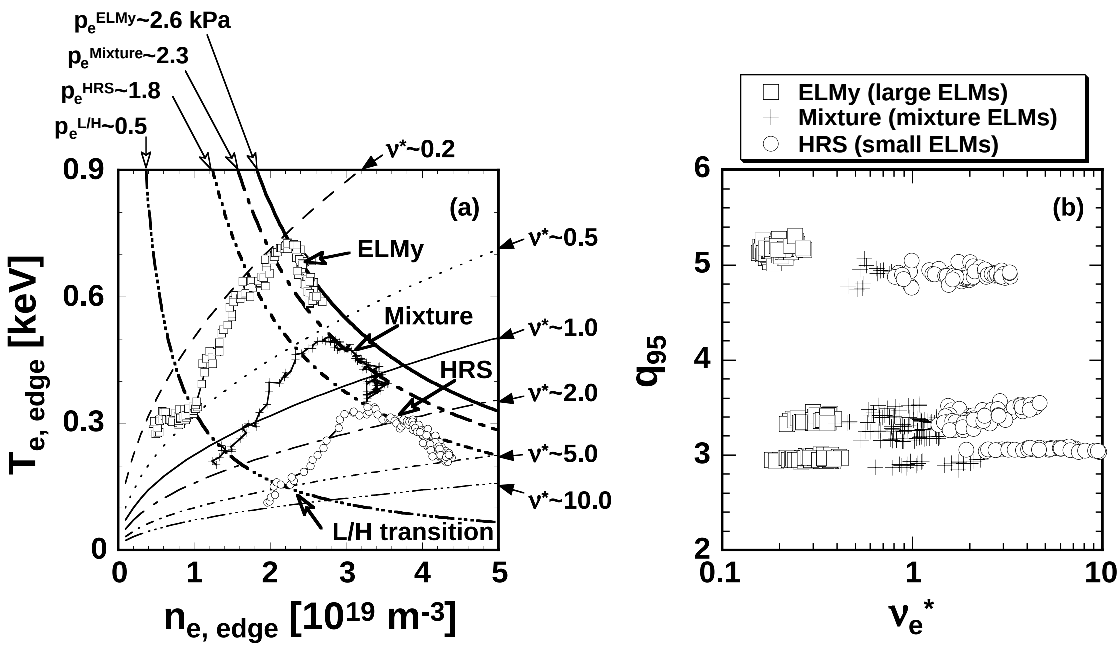

FIG. 2. (a) n-T diagram for ELMy/Mixture/HRS discharges and (b) operational regimes in q_{95}-ν_e^* space.

It is also noted that the L/H transitions of all three discharges occur at the nearly constant pressure line at p_e~0.5 kPa in the edge n_e-T_e space. However, the trajectories in n_e-T_e space during ELM-free periods follow different collisionality regimes (e.g. ELMy (#99937); ν_e^*<1, Mixture (#99940); ν_e^*~1, and HRS (#99941); ν_e^*>1). The achieved edge pressure at the end of the ELM-free period in the ELMy discharge (#99937; p_e^{ELMy}~2.6 kPa) is about 30% higher than the HRS discharge (p_e^{HRS}~1.8 kPa). The Mixture discharge also reaches an intermediate edge pressure of $p_e^{Mixture}$~2.3 kPa, between ELMy and HRS discharges. One can expect that the ELMy discharge reaches a *critical* edge pressure value during its ELM-free period [12, 13]. After exceeding a *critical* value, large (similar to Type-I) ELMs appear, and then the pedestal keeps a nearly constant edge pressure line. On the other hand, the HRS discharge also seems to be limited by its own *critical* edge pressure value of about 30% lower than that of ELMy discharge. The pedestal in the HRS discharge also keeps a nearly constant edge pressure line, caused by the small and high frequency ELM activities seen on top of the enhanced D_α signal.

To investigate the access conditions for ELMy/Mixture/HRS discharges, parameters scan were performed in q_{95}-ν_e* space. As shown in Fig. 2 (b), most "ELMy" discharges having large ELMs are clearly classified as the collisionless regime of ν_e^*<1 even at higher q_{95}. Again, a marginal regime exists near the ELMy/HRS operational boundary. In higher q_{95}~5, it seems to be more easily to access the *pure* "HRS" regime at around ν_e^*~1, while the "Mixture" regime extends its operational regime toward the collisional regime of $\nu_e^* \geq 1$ at lower q_{95}~3. These results imply the importance of both q_{95} and ν_e^* to understand the access conditions for the HRS regime.

2.3. Precursors and fluctuations

In almost all HRS discharges, edge MHD activities are observed on the magnetic probes at the vessel wall in the frequency range of the order of 10-100 kHz, which rotate in the direction counter to the plasma current. These are also observed in the ELMy discharges during ELM-free and between ELMs phases, although their amplitude, frequency range, and mode number show different features in comparison with HRS plasmas.

As observed in Fig. 3, a coherent magnetic fluctuation with higher frequency at around f~350-450 kHz (HF-mode) appears at the onset of the jump in D_α signal in the HRS discharge. Note that the toroidal and approximate poloidal mode numbers are determined using the magnetic probe array in the vessel wall as n~7 and m≥10, respectively. It is considered that the presence of the edge MHD activities may keep an edge pressure below a certain level needed to induce a large ELM. The base level of the D_α signal during ELMs activities make it possible to distinct HRS from ELMy discharges. The latter lies in the ELM-free level, but the former is a few times higher than ELM-free (or L-mode) level. It is suggested that these MHD activities associated with the HRS may also important for an enhanced particle transport.

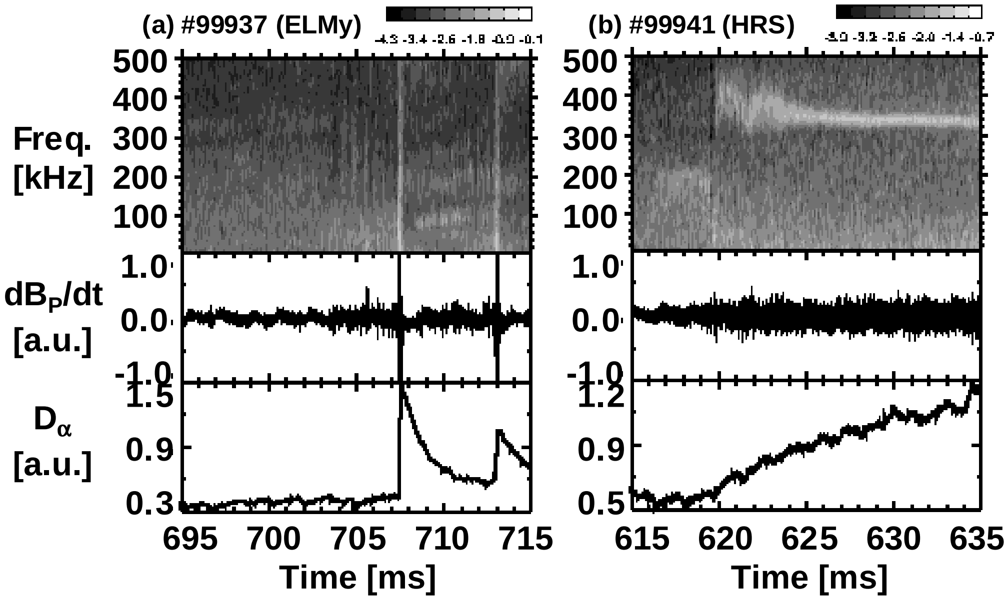

FIG. 3. Edge MHD activities in (a) ELMy and (b) HRS discharges.

3. Effects of plasma shape

3.1. Enhanced confinement and stability in highly shaped HRS plasmas

It is well known that the plasma shaping could affect the confinement and stability, especially in the characteristics of H-mode performance including ELM behaviors, as seen in Type-II and "Grassy" ELMs [2, 14, 15]. Since the HRS H-mode is observed only at $n_e/n_{GW} \geq 0.4$ (or $\nu_e^* \geq 1$) so far, a key issue for HRS H-mode studies is to extend its operational regime toward $n_e/n_{GW} \leq 0.4$ (or $\nu_e^* \leq 1$) and enhancement in the energy confinement utilizing the capability of both high triangularity $\delta \geq 0.7$ and elongation $\kappa \geq 1.6$ operation under the double-null (DN) configuration.

As shown in Fig. 4, the global energy confinement in HRS plasmas using the DN configuration was found to be systematically better than the SN configuration. The HRS regime with the DN configuration also made it possible to extend toward lower density region ($0.3 \leq n_e/n_{GW} \leq 0.4$), where the large ELMs appeared under the moderate shaping in the SN configuration. These results may be related to larger effect on the ELM stabilization due to the strong plasma shaping in the DN configuration, increasing the H_{89P} up to ~2 at around n_e/n_{GW}~0.4, which was comparable to that of the standard ELMy H-mode regime having large ELMs under the SN configuration. However, there was a confinement degradation slightly with density (especially, at $n_e/n_{GW} \geq 0.5$) at both DN and SN configurations, which may be related to the increase in the neutral pressure at the plasma edge region as shown in Ref. [7, 8].

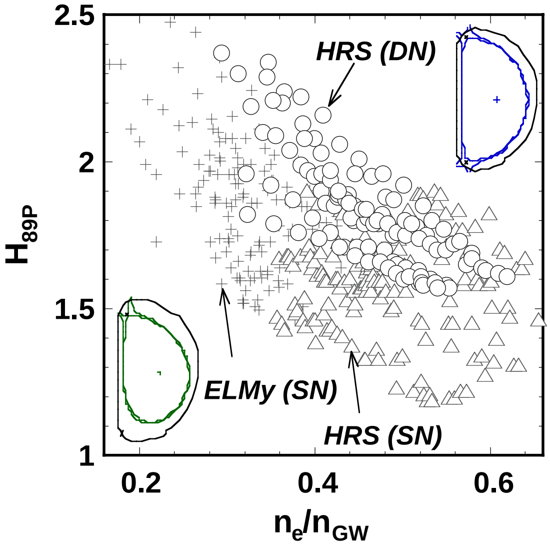

FIG. 4. H_{89P} plotted versus n_e/n_{GW}.

3.2. Parameters scan in q_{95}-δ space

Since we found that the access condition to the HRS regime is affected by both q_{95} and δ as written in Sec. 2.2 and 3.1, parameters scan in the q_{95}-δ space were performed to understand the shaping effect clearly. Comparing between single-null (SN) and Limiter (LIM) configurations, the latter makes it possible to scan widely in the q_{95}-δ space. Since first discovered on JFT-2M [16], it is recognized that the H-mode plasmas can be produced under the limiter configurations without any null-point (so called "Limiter H-mode"). And we could distinguish HRS from ELMy H-mode even at the limiter configurations as the presence of same edge MHD activities that are shown in Sec. 2.3, in addition to the ELM activities.

As a result, we could easily access to the HRS regime in the D-shaped plasma as shown in Fig. 5 (e.g. #99032 or #100033). On the contrary, large ELMs (probably, Type-III ELMs) appeared in the circular cross-sectional shape even at high density/recycling condition (e.g. #99025). Although we could not directly extrapolate these dependences at the divertor configurations, these results suggest that not only density (and/or neutrals) but also plasma shape plays an important role to access the HRS regime.

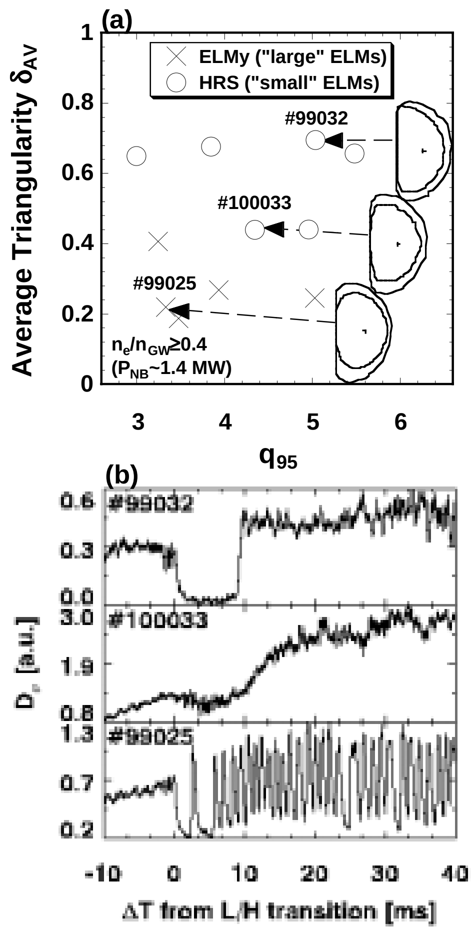

FIG. 5. (a) ELMy and HRS operational regimes in q_{95}-δ space. (b) D_a emissions in different q_{95}-δ space are also shown.

4. Heat load to the divertor target

The heat flux (Γ_{heat}) to the divertor targets was estimated by means of the Langmuir probes in SOL on the target plates [17]. As shown in Fig. 6, both electron temperature $T_{e,div}$ and ion saturation current $I_{S,div}$ on the divertor plate increase rapidly during ELM event, showing a significant arrival of both heat and particle fluxes to the divertor. On the contrary, the HRS plasma shows that the $I_{S,div}$ solely increase, keeping the $T_{e,div}$ low value at ~10 eV. We can evaluate the Γ_{heat} as $\gamma J_{S,div} T_{e,div}$. Here the $J_{S,div}$ is ion saturation current density and γ (~7 for the parameters on JFT-2M) is a heat transmission coefficient [18]. As a result, the Γ_{heat} in the HRS discharge was about ~0.3 MW/m^2, which was only ~15% of that for ELM event. Another observation at the divertor region is the 2D measurement of the D_α emission utilizing the fast framing CCD camera. As shown in Fig. 6, we found that an intense and pulsed D_α emission were localized around the hit-point of the divertor plate at the onset of large ELM in the ELMy discharge (#98851), while the HRS discharge exhibited a uniformly enhanced D_α emission (#99386). The latter makes it possible to mitigate the local transient heat load to the divertor target, extending the lifetime of the divertor plate.

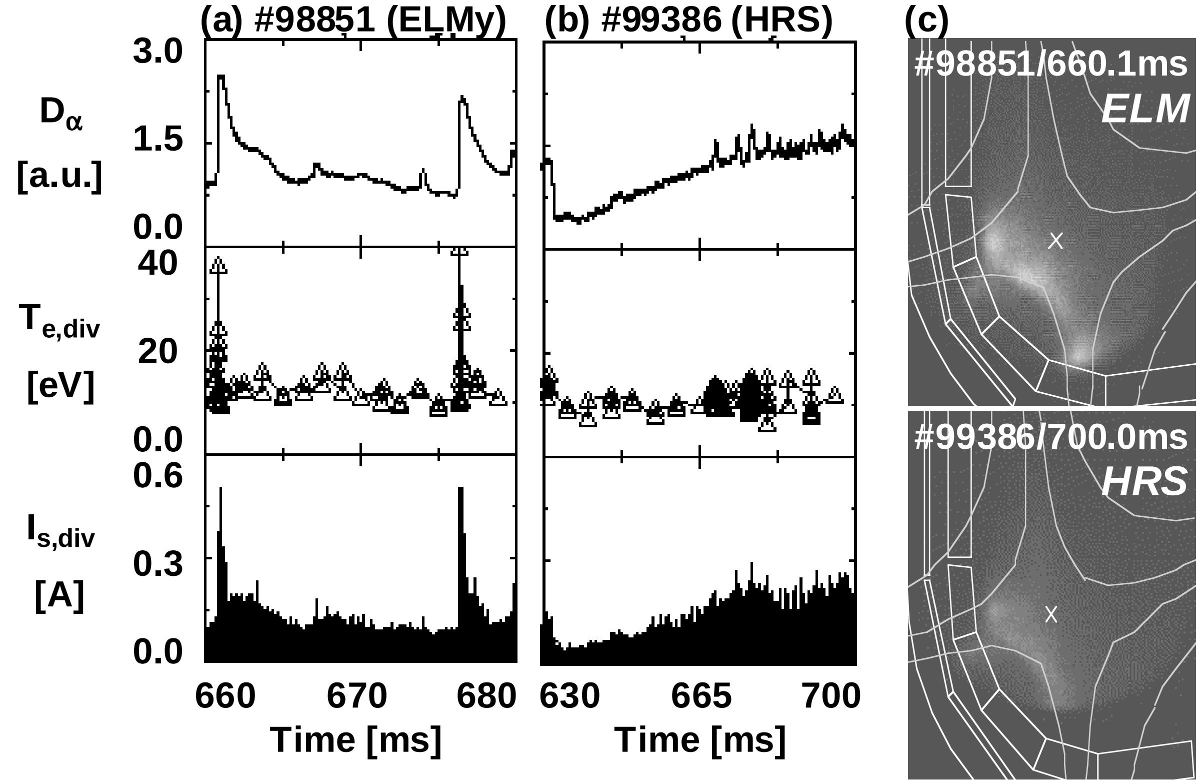

FIG. 6. Comparison of plasma boundary parameters for (a) ELMy and (b) HRS H-modes. (c) The 2D images of D_a emission profile measured by fast CCD camera are also shown. The viewing chord of CCD camera is tangential.

5. Summary

In this paper, we investigated the access conditions for the HRS regime in terms of the pedestal parameters. It was found that the dimensionless parameters, such as ν_e^*, q_{95} in addition to plasma shaping, were important to understand the operational regime. Access to HRS regime was again favored by higher density and/or neutral pressure. The effect of plasma shaping was also confirmed to play a role for the enhanced confinement and stability.

These features seen in the HRS regime reported here seem to be very similar to the

"EDA" regime on Alcator C-Mod [19], although some differences are also found (e.g. somewhat higher toroidal/poloidal mode numbers in the associated fluctuations for EDA). It may come from the slightly unmatched other dimensionless parameters and/or the differences in the heating method. In order to establish a better understanding of the relation between the EDA and HRS regimes, a systematic comparison between C-Mod and JFT-2M at matched plasma shape has been started. Detailed comparison in terms of access conditions, fluctuation characteristics and global parameters will be performed.

A key feature in the HRS H-mode plasma is a possibility of the reduction of the transient heat loads to the divertor target due to large ELMs. It was estimated to be about ~0.3 MW/m^2 in HRS discharge, which was about ~15% of that for ELM event. In this study, it is suggested that the appearance of edge MHD activities may keep the edge pressure (or gradient) below the level needed to induce a large ELM. This activity is also believed to be important for both enhanced particle transport and stationary H-mode edge conditions in the absence of large ELMs.

Acknowledgments

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References

[1] Rice. J. E., et al., "Double transport barrier plasmas in Alcator C-Mod". Nucl. Fusion **42** (2002) 510.

[2] Sips. A. C. C., et al., "Progress towards steady-state advanced scenarios in ASDEX Upgrade". Plasma Phys. Control. Fusion **44** (2002) A151.

[3] Greenfield. C. M., et al., "Quiescent Double Barrier Regime in the DIII-D Tokamak". Phys. Rev. Lett. **86** (2001) 4544.

[4] Ongena. J., et al., "Recent progress on JET towards the ITER reference mode of operation at high density". Plasma Phys. Control. Fusion **43** (2001) A11.

[5] Kamada. Y., et al., "Pedestal characteristics and extended high-βp ELMy H-mode regime in JT-60U". Plasma Phys. Control. Fusion **44** (2002) A279.

[6] Ninomiya. H., et al., "Research Activities on Tokamaks in Japan: JT-60U, JFT-2M, and TRIAM-1M". Fusion Science and Technology **42** (2002) 7.

[7] Kamiya. K., et al., "Observation of High Recycling Steady H-mode Edge and Compatibility with Improved Core Confinement Mode on JFT-2M". Nucl. Fusion **43** (2003) 1214.

[8] Kamiya. K., et al., "High Recycling Steady H-mode Regime in the JFT-2M Tokamak". Plasma Phys. Control. Fusion **46** (2004) A157.

[9] Kamiya. K., et al., "Pedestal characteristics in JFT-2M HRS H-mode plasma". Plasma Phys. Control. Fusion **46** (2004) 1745.

[10] ITER Physics Expert Groups on Confinement and Transport and Confinement Modelling and Database, and ITER Physics Basis Editors, "Chapter 2: Plasma confinement and transport". Nucl. Fusion **39** (1999) 2175.

[11] Greenwald. M., et al., "A new look at density limits in tokamaks". Nucl. Fusion **28** (1988) 2199.

[12] Connor. J. W., "Edge-localized modes - physics and theory". Plasma Phys. Control. Fusion **40** (1998) 531.

[13] Suttrop. W., “The physics of large and small edge localized modes”. Plasma Phys. Control. Fusion **42** (2000) A1.
[14] Ozeki. T., et al., “Plasma shaping, edge ballooning stability and ELM behaviour in DIII-D”. Nucl. Fusion **30** (1990) 1425.
[15] Kamada. Y., et al., “Onset condition for ELMs in JT-60U”. Plasma Phys. Control. Fusion **38** (1996) 1387.
[16] Odajima. K., et al., “Confinement studies of additionally heated plasmain the JFT-2M tokamak”. Fusion Energy 1986 (Proc. 11th Int. Conf. Kyoto, 1986), IAEA, Vienna, 151 (1987).
[17] Kawashima. H., et al., “Comparing divertor recycling and heat flux in JFT-2M ELMy and HRS H-mode discharges”. J. Plasma Fusion Res.
[18] Stangeby. P. C., et al., “Plasma boundary phenomena in tokamaks”. Nucl. Fusion **30** (1990) 1255.
[19] Hughes. J. W., et al., “Observations and empirical scalings of the high-confinement mode pedestal on Alcator C-Mod”. Phys. Plasmas **9** (2002) 3019.