THERMAL ENERGY CONFINEMENT OF HIGH TRIANGULARITY ELMY H-MODE PLASMAS IN JT-60U

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1. Introduction

ELMy H-modes are currently considered the most promising plasma operating regime of enhanced confinement with a proven capability for steady state performance in a future reactor-size magnetic fusion experiment. In order to achieve the required fusion yield, any next-step machine needs to operate at a high density. The projection of the performance of ELMy H-mode plasmas to ITER-FEAT [1] also shows that the plasma density required to achieve a high fusion power gain is near the Greenwald density limit, n^{GW}. However, it has generally been seen that core confinement quality is diminished continuously as the density is increased by gas fuelling in many devices [2-4]. Recently, the temperature at the pedestal shoulder imposed by regular ELM events is considered to play a role as a boundary condition in determining the profile of the core temperature [3,5-9]. High triangularity discharges, in which the critical edge pressure gradient can be raised, are therefore expected to bring on the high improved energy confinement of the plasma core [2,10-12]. The improved energy confinement has also been achieved in high β_{pol} H-mode discharges with an internal transport barrier (ITB) at high triangularity [13].

2. Experiments

The experiments were performed at the plasma current, I_p = 1.0 MA. The toroidal magnetic field, B_t = 2.1 T and q_{95} = 3.4-3.6. The neutral beam (NB) injection power, P_{NBI}, for deuterium plasma was in the range of 9.0-11.5 MW at the relevant time of analysis. With deuterium gas puffing, $\bar{n}_e$, was varied on a shot by shot basis from 1.8×10^{19} to 3.2×10^{19} m^{-3}. Elongation, κ, of 1.4 and triangularity, δ_x, of 0.45 were fixed. The plasma volume, V_p, was in the range of 55-56 m^3. The plasma major radius, R_p = 3.3 m and the minor radius, a_p = 0.82 m. In order to assess the effects of triangularity, low triangularity discharges were also carried out at δ_x = 0.20. In this case, n^{GW} ~ 5.0×10^{19} m^{-3} because of a_p = 0.79 m, whereas n^{GW} ~ 4.7×10^{19} m^{-3} at δ_x = 0.45.

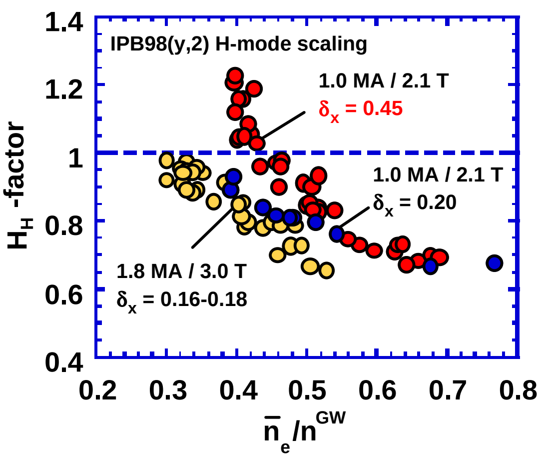

Fig. 1 The H_H-factor for ELMy H-mode discharges in JT-60U as a function of $\bar{n}_e/n^{GW}$.

3. Thermal energy confinement properties

Figure 1 displays the H_H-factor based on the predictions of the IPB98(y,2) scaling as a function of $\bar{n}_e/n^{GW}$. For reference, figure 1 also includes data from the density scan experiments of the low triangularity ELMy H-mode (I_p = 1.8 MA, B_t = 3.0 T, q_{95} = 3.0, δ_x = 0.16 and P_{NBI} = 8-13 MW) [7]. It is seen most clearly that the thermal energy confinement is improved by high triangularity discharges at low densities. The discharges in steady state at low densities are characterized by type-I ELMs. In the high density regime type-III-like ELMs are generated at high triangularity. Compared to low triangularity case, higher ELM frequency is observed at a given density.

Profiles of n_e and T_i for low and high triangularity plasmas with P_{NBI} = 9.0 MW at a fixed density of $\bar{n}_e/n^{GW}$ ~ 0.40 are shown in figure 2(a) and (b). It is seen in figure 2(a) that the density profiles are similar in either case. It is the fact that the core temperature is also improved by a factor of ~ 1.3 as well as the peripheral temperature (see figure 2(d)) by high triangularity discharge that is of most significance because the plasma shaping affects strongly edge toroidal magnetic flux surfaces as seen in figure 2(b). Thus, there seems to exist a large transport structure where the core temperature is determined by a boundary value. As is shown in figure 2(c), the profiles of temperature, on a log scale, are stiff in the sense that there is a minimum scale length of temperature gradient,

$$L_T = \left[\frac{1}{T}\frac{dT}{dr}\right]^{-1} = \left[\frac{d(\ln T)}{dr}\right]^{-1} \qquad (1)$$

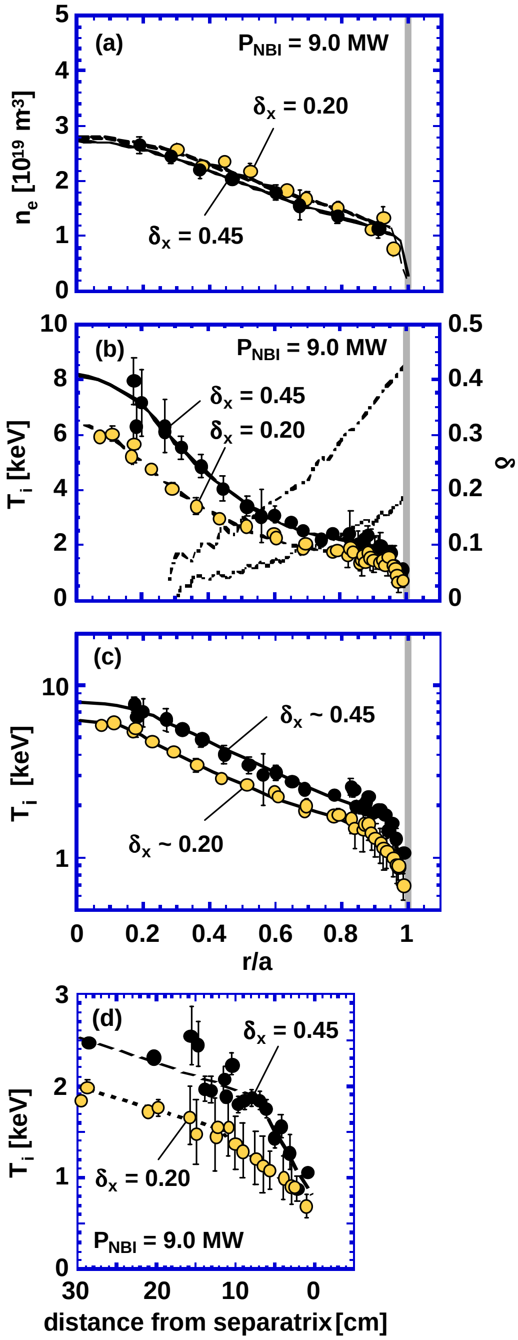

Fig. 2 Profiles of (a) n_e, (b) T_i on a linear scale and (c) T_i on a log scale for low and high triangularity discharges at a fixed density ($\bar{n}_e/n^{GW}$ ~ 0.40). (d) The pedestal T_i profiles are also shown.

which can be achieved and the energy transport adjusts to maintain this scale length [6]. A similar behavior is observed for electron temperature profiles. Since the temperature at the shoulder of the H-mode pedestal is raised by high triangularity, the core temperature may be increased due to the effect of profile stiffness.

4. Pedestal characteristics

As seen in figure 2(b), triangularity affects directly the edge toroidal magnetic flux surfaces. In this section, the pedestal structure imposed by the ELM activities is examined for the case of low and high triangularity. A comparison of the pedestal characteristics between low and high triangularity ELMy H-mode plasmas is shown as a diagram for the pedestal density and temperature in figure 3(a). At fixed I_p of 1.0 MA, the high triangularity ELMy H-mode plasmas produce the pedestal temperature higher than that of low triangularity plasmas at a given density. Besides, it is seen in high triangularity plasmas that the pedestal pressure tends to decrease gradually with density. Figure 3(a) also shows a time trace of the pedestal for a high β_{pol} ELMy H-mode discharge with ITB due to high power additional heating. On the high triangularity configuration, it can be seen that the high β_{pol} H-mode plasma reaches the higher critical pedestal pressure. Related to this respect, the dependence of the pedestal poloidal beta, $\beta_{pol}{}^{ped}$, upon triangularity is plotted in figure 3(b). A comparison of standard ELMy H-modes without ITB between low and high triangularity discharges indicates that $\beta_{pol}{}^{ped}$ tends to increase gradually with increasing triangularity. In high β_{pol} H-mode plasmas, the pedestal confinement is improved further at high triangularity, and thus significantly high confinement coupled with the core improvement due to ITB is obtained.

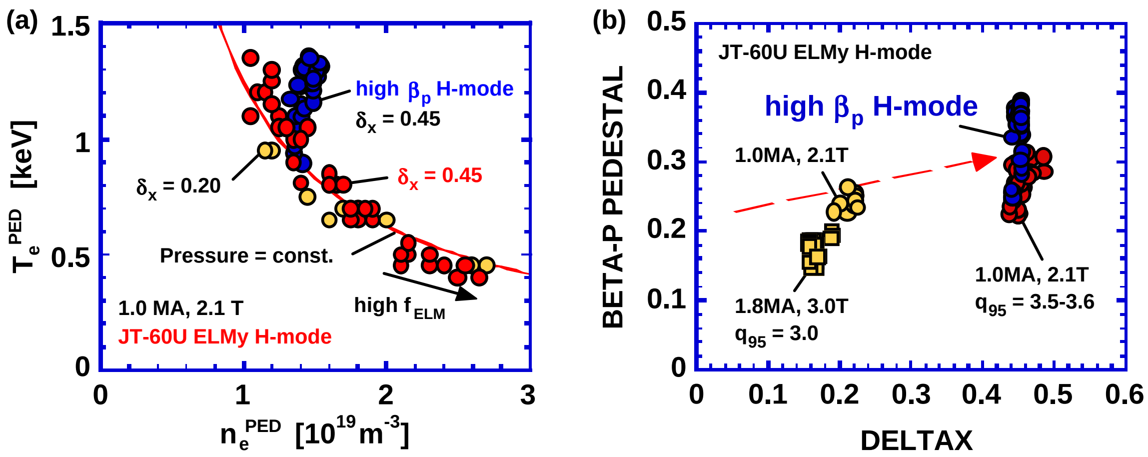

Fig. 3 (a) Relation between the pedestal density and temperature in ELMy H-mode plasmas (b) Dependence of the poloidal beta at the pedestal on triangularity.

5. Boundary condition for thermal energy confinement

It has been identified in many tokamaks that the thermal energy confinement in H-mode plasmas depends strongly upon the temperature at the shoulder of the H-mode pedestal [3,5-9]. In the standard ELMy H-mode without ITB, the profile similarity in the temperature, which is also expected from figure 2(c), is shown in figure 4. The core temperature (r/a_p ~ 0.3) increases in approximately proportion to the pedestal temperature for each species. At a fixed I_p of 1.0 MA, this edge-core relationship in high triangularity plasmas is conformed consistently with low triangularity case. The pedestal temperature may be a key boundary factor for the core energy confinement through the stiff profile of temperature. Higher triangularity plasma has the higher temperature at the pedestal shoulder determined by the ELM activities at a given density, which in turn leads to an increase in the core temperature, resulting in the improvement of the energy confinement of H-mode plasmas.

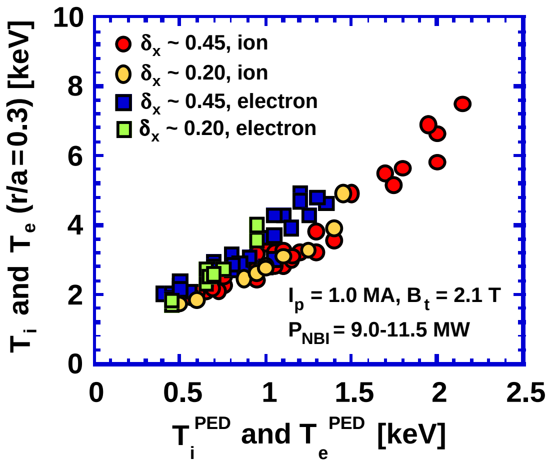

Fig. 4 Profile similarity of temperatures for each species in JT-60U ELMy H-mode plasmas.

6. Conclusions

The density scans of the energy confinement and pedestal properties were carried out in high and low triangularity ELMy H-mode plasmas on JT-60U. High triangularity discharges produced the higher pedestal pressure, at which higher pedestal temperature was obtained at a given density. The core temperature increases in roughly proportion to the pedestal temperature for each species, independent of triangularity. High β_{pol} H-mode plasmas due to high power heating produced further high pedestal confinement. The improvement of the edge stability by triangularity leads to higher pedestal temperature, which in turn raises the core temperature, and thus the high thermal energy confinement is obtained.

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