Substantial Reduction of H-mode Transition Threshold Power in JT-60U

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Abstract. Substantial reduction of the H-mode transition threshold power was observed under the W-shaped divertor in JT-60U, in comparison with the open divertor. Radiation power in main region was also decreased in this case. These difference of radiation power from the main plasma between open and W-shaped divertor was not large enough to account for the apparent reduction of threshold power. In this study, the edge plasma parameters which relate to L-H transition were put emphasis on. It was found that edge ion temperature at which L-H transition occurred in the open divertor case was established by lower input power since edge density became smaller in the W-shaped divertor case under the condition of the same line-averaged density. After the modification of divertor geometry, ion edge collisionality just before L-H transition became lower and it was established with lower auxiliary power input. It was suggested that reduction of edge ion collisionality arose from neutral particles near the X-point by the analysis of poloidal profile of neutral density. Therefore, after the modification of divertor geometry, threshold power decreased though edge neutral density became larger.

1. Introduction

The JT-60U divertor geometry was recently modified to W-shape with pumping capability from both sides of the septum in the private region, for the effective particle and heat flux control. In the open divertor case, effect of neutral particles for L-H transition was studied, and it was obtained that edge ion collisionality just before L-H transition became smaller with increasing neutral density.[1] In the W-shaped divertor, threshold power reduction was obtained. The cause of this reduction was investigated from the viewpoint of edge plasma condition which seemed to be affected due to the modification of divertor geometry.

2. Reduction of L-H Transition Power in W-shaped divertor

As shown in Fig.1, particle can be exhausted through the two slots at inside and outside with $16\mathrm{m}^3$/s of pumping speed. The systematic density scan (up to 60% of Greenwald density) was carried out in order to investigate density dependence of threshold power.[2] Figure 2 shows the typical waveforms in a shot of this experiment series. The neutral beam (NB) input power was varied in a stairway fashion to improve the resolution of the threshold power. Plasma configuration was kept in both case (V_P~$60\mathrm{m}^3$), as illustrated in Fig.1. H-mode transition was considered to occur at the timing denoted by dotted line in Fig.2. This main criterion was Dα drop and rising of density and stored energy. Figure 3 shows the threshold power as a function of line-averaged density in the both cases of open and W-shaped divertor geometries. P_{LOSS} denotes $P_{\mathrm{IN}}+P_{\mathrm{OH}}-\mathrm{d}W/\mathrm{d}t$. This value is equivalent to the power flowing toward plasma edge. P_{IN} means net power into plasmas by NB. Putting emphasis on the density dependence, vertical axis value was normalised by B_T because threshold power was linearly proportional to B_T.[3,4] In this campaign, remarkable reduction of the H-mode threshold power of more than 30% was observed in the region $\bar{n}_e=2\sim3\times10^{19}\mathrm{m}^{-3}$ in compared with the open divertor case. The

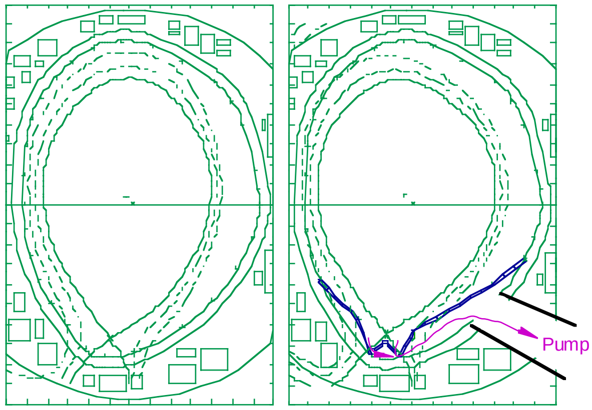

FIG.1. Comparisons of divertor geometry and plasma configuration between open (left) and W-shaped (right) divertor cases.

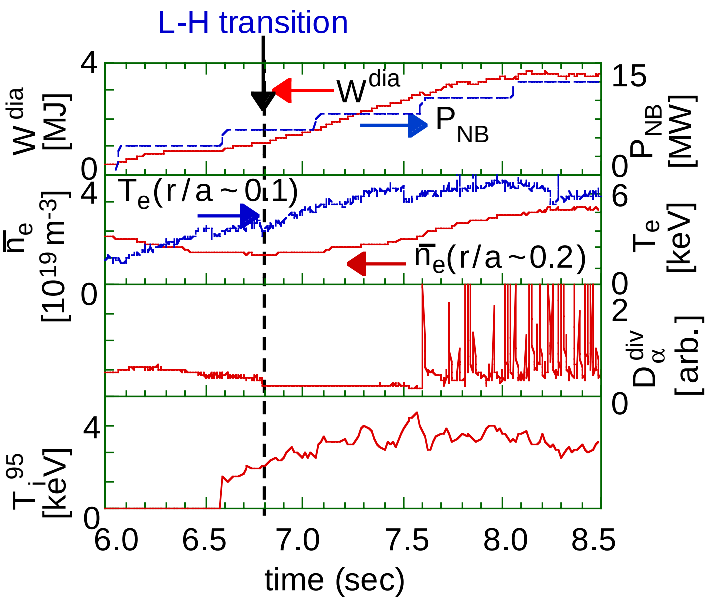

FIG.2. Typical waveforms in the experiment series for H-mode study. H-mode transition occurs at the timing denoted by dotted line.

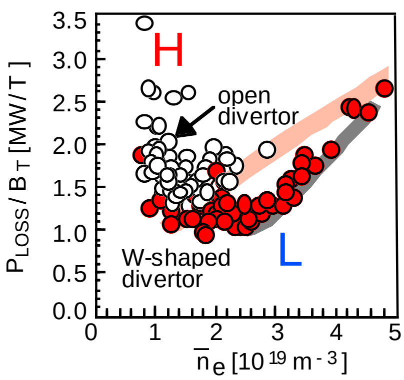

FIG.3. Dependence of threshold power on line averaged density in both divertor cases.

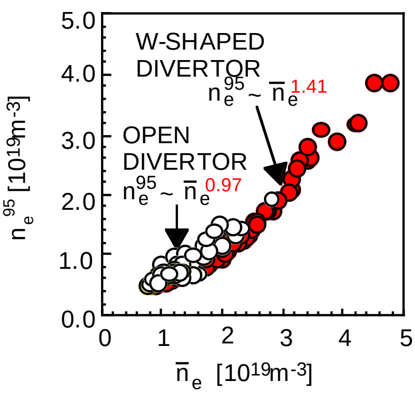

FIG.4. Dependence of edge density on line-averaged density became stronger after modification of divertor.

loss power by radiation from main plasma was smaller than that in the open divertor. However, difference of the radiation power between the open and the W-shaped divertors is not large enough to account for the apparent reduction of around 30%, corresponding to reduction of $Z_{\rm eff}$. Hence, we focused on the analysis of edge parameters which significantly related to L-H transition.

3. Behaviour of edge plasma parameters for L-H transition

In the W-shaped divertor case, it was found that line-averaged density dependence of threshold power became stronger than linear ($\sim\bar{n}_{\rm e}^{1.1\text{-}1.3}$), whereas the density exponent remained at 0.5~0.75 in the open divertor.[5] Heuristic feature clarified in this work is that different dependence on line-averaged density under different divertor geometries is integrated in scaling in terms of the edge density. Figure 4 shows dependence of edge density on line-averaged density became stronger after modification of divertor. After the modification of divertor geometry, edge density became lower than hat in the open divertor case at the same line-averaged density. Figure 5 shows that the threshold powers for both geometries can be indeed scaled with $(n_{\rm e}^{95})^{0.75}$, although the scaling factor is much smaller for the W-shaped divertor (A(open)=1.15, A(W)=0.75). This result denotes that edge density, instead of averaged density, should be employed for analysis and extrapolation of the database to ITER-FEAT.[2]

Figure 6 shows edge density dependence of $Z_{\rm eff}$ and edge ion temperature. $Z_{\rm eff}$ became clearly smaller in the W-shaped divertor case under the condition of $n_{\rm e}^{95}>1.0\times10^{19}{\rm m}^{-3}$ where $P_{\rm LOSS}$ followed the scaling shown in Fig.5. This contributed to the reduction of radiation power from main plasma. Edge ion temperature in the region of $n_{\rm e}^{95}=1.0\sim1.5\times10^{19}{\rm m}^{-3}$ shows similar value in both divertor cases. This means that edge ion temperature which induce L-H transition in the open divertor case was established by lower input power since edge density became smaller after the modification of divertor.

In JT-60U, H-mode transition normally occurred when ion collisionality at plasma edge ($\nu^*_{\rm i\ eff}$) is around unity. $\nu^*_{\rm i\ eff}$ defined as follows[6,7]:

$$\nu^*_{\rm i\ eff} = \frac{n_{\rm e}}{n_{\rm i}}\frac{Z_{\rm eff}}{Z_{\rm i}^2}\frac{\nu_{\rm ii}}{\nu_{\rm b}} = \frac{n_{\rm e}}{n_{\rm i}}\frac{Z_{\rm eff}}{Z_{\rm i}^2}\frac{16\sqrt{\pi}n_{\rm i}e^4\ln\Lambda Z_{\rm i}^4}{3\varepsilon m^{1/2}(2T)^{3/2}}\left[\frac{\varepsilon^{1/2}}{qR}\left(\frac{2T}{m}\right)^{1/2}\right]^{-1}$$

After the modification of divertor geometry, $\nu^*_{\rm i\ eff}$ right before H-mode transition ($\nu^*_{\rm i\ eff}$(L-H)) became smaller at $n_{\rm e}^{95}<1.5\times10^{19}{\rm m}^{-3}$ as shown in Fig.7. This means that low edge ion collisionality was established with lower input power, whereas L-H transition becomes easy to occur in this density region in the case of W-shaped divertor.

4. Relation between neutral particle and edge ion collisionality

In order to clarify the reason why $\nu^*_{\rm i\ eff}$(L-H) was reduced, we have investigated the effect of neutral particles of which the inconvenient role for H-mode transition is theoretically predicted.[8,9] We tried to analysis the relation between edge neutral density and $\nu^*_{\rm i\ eff}$(L-H) in W-shaped divertor case, as well as the open divertor case.[1] Edge neutral density used in this analysis was estimated by DEGAS code.[10] Edge plasma parameters as the input parameter of DEGAS were calculated with the interpretative divertor code[11] using the measured data by Langmuir probe array settled on the divertor plates. The absolute value of neutral density was adjusted to be consistent with the Dα intensity. Here, we discuss the effect of neutral particle with the method to evaluate the poloidal distribution of edge neutral density. Figure 8 show the relations between $\nu_{i\ \mathrm{eff}}^{*}$(L-H) and the ratio of neutral and electron densities (a)near the X-point and (b)at midplane. Near the X-point, $\nu_{i\ \mathrm{eff}}^{*}$(L-H) became smaller with edge neutral density whereas no clear correlation was obtained at midplane. These results indicates that neutral particle near the X-point could play a main role of preventing L-H transition since low $\nu_{i\ \mathrm{eff}}^{*}$(L-H) means the L-H transition becomes hard.

Figure 9 shows relation of edge ion collisionality and threshold power in the region of n_e^{95}=1.0~1.5×10^{19}m^{-3} where P_{LOSS} drastically decreased after the modification of divertor geometry. In the W-shaped divertor case, lower threshold power obtained under the condition of low ion edge collisionality which was affected by neutral density near the X-point. Data group in W-shaped divertor case was shifted to lower $\nu_{i\ \mathrm{eff}}^{*}$(L-H) in comparison with open divertor case. This effect was caused by neutral particles near the X-point which were able to be easily condensed toward near the X-point. As the result, after the modification of divertor geometry, threshold power decreased although edge neutral density near the X-point became larger.

5. Summary

In JT-60U, we obtained the decrease of threshold power after the modification of divertor geometry, in comparison with the open divertor case. Regarding this phenomenon, we tried to discuss from the viewpoint of edge parameters. This main reason was that edge ion temperature at which L-H transition occurred in the open divertor case was established by lower input power since edge density became smaller after the modification of divertor. In the case of W-shaped divertor, lower edge ion collisionality just before H-mode transition was established with lower input power in comparison with open divertor case. It was suggested that edge ion collisionality reduction arose from neutral particles near the X-point by the analysis of poloidal profile of neutral density.

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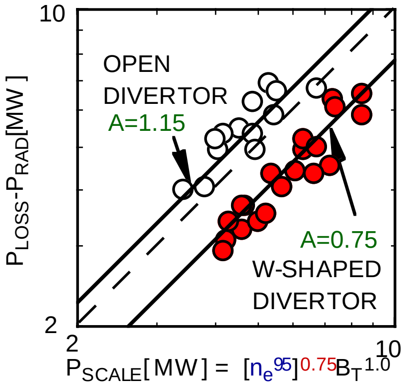

FIG.5. Edge density dependence of threshold power. This exponent is 0.75 in both divertor geometries.

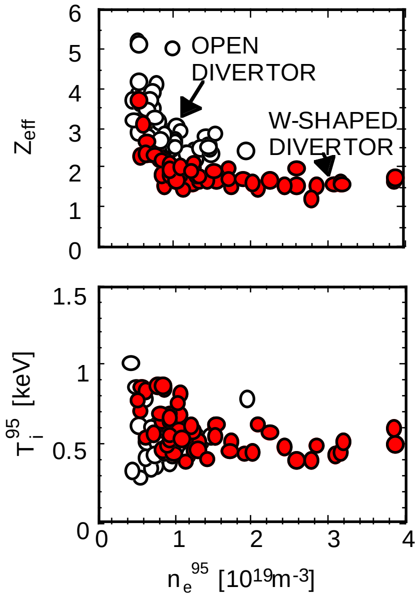

FIG.6. Edge density dependence of Z_{eff} (left) and edge ion temperature(right). Z_{eff} became clearly smaller in the W-shaped divertor case under the condition of n_e^{95}>1.0×10^{19}m^{-3} where P_{LOSS} followed the scaling. T_i^{95} in the region of n_e^{95}=1.0 ~1.5×10^{19}m^{-3} shows similar value in both divertor cases.

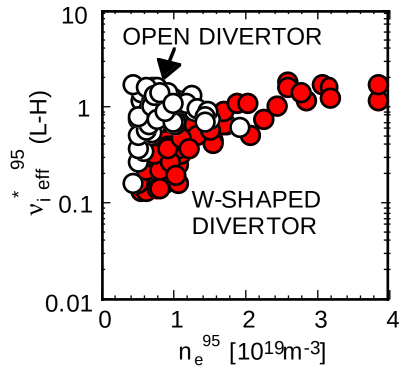

FIG.7. Edge density dependence of edge ion collisionality. In W-shaped divertor case, low ion collisionality was established by the lower input power.

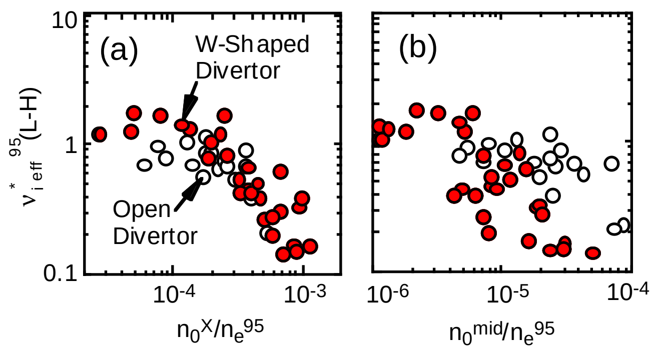

FIG.8. Relations between edge ion collisionality and the ratio of neutral and electron densities (a)near the X-point and (b)at midplane. Near the X-point, ion edge collisionality became smaller with edge neutral density whereas no clear correlation was obtained at midplane.

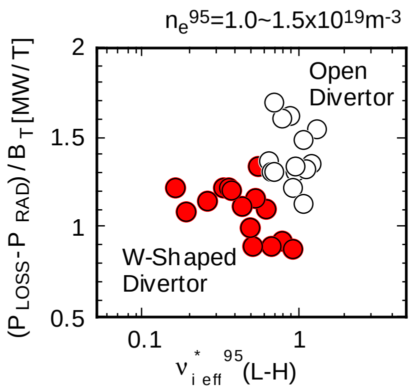

FIG.9. Relation of edge ion collisionality and threshold power. In the W-shaped divertor case, lower threshold power obtained under the condition of low ion edge collisionality which was affected by neutral density near the X-point.