

Behaviour of divertor neutral pressure during the divertor detachment in the pumped W-shaped divertor of JT-60U

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1. Introduction

In the steady operation of fusion reactor, the high performance in the core plasma and the reduction of heat load on the divertor plates should be simultaneously realised. In order to reduce the heat load on the divertor plates, detachment of divertor plasma is necessary. Such a divertor detachment is achieved by an intense gas puffing. However, this divertor detachment often induces an X-point MARFE, which is characterised by enhanced radiation power loss around the X-point and causes a degradation of the energy confinement in the core plasma. Therefore, a detached divertor plasma at both sides of the divertor plates should be maintained without inducing an X-point MARFE [1].

This paper reports the measurements of the divertor neutral pressure profile during the detached divertor and at the onset of an X-point MARFE [2], and proposes the control to sustain the detached divertor without inducing an X-point MARFE performed in JT-60U.

2. Divertor detachment and X-point MARFE

Figure 1 illustrates the location of the fast-response ionisation gauges, lines of sight of bolometer array and Langmuir probes for the divertor diagnostic.

Divertor neutral pressure is measured by fast-response ionisation gauges, which were developed by the ASDEX team [3]. In front of each gauge head, a chevron is placed in order to avoid plasma exposure and to provide thermalisation of particles. The time response of pressure measurement, including the effect of the chevron, is about 3ms.

Figure 2 shows the temporal evolution of line averaged electron density, n_e^{ave} , gas puff rate from the top of main chamber, divertor radiation power loss, P_r^{div} , neutral beam power, ion saturation current of the Langmuir probes at the inner and outer strike points, neutral pressures at the inner and outer private regions. These parameters were measured during the density rise phase resulting from an intense gas puff up to $30 \text{ Pa m}^3/\text{s}$. The gas puff was injected during the ELMy H-mode phase of the plasma with plasma current 1 MA, toroidal magnetic field 3.8 T, $q_{eff}=8.3$ and an X-point height of 6 cm from the top of the dome.

Detachment of the divertor plasma is estimated from the ion saturation current of the Langmuir probes at the strike points. Detachment at the inner strike point starts in the earlier phase of density rise up. On the other hand, detachment at the outer strike point starts at 7.1 s. Then, an X-point MARFE starts at 7.37s, which is characterised by an increase in P_r^{div} due to an increase in the X-point radiation. n_e^{ave} also increases at the X-point MARFE. Though the detachment of the divertor plasma still occurs at the both sides during an X-point MARFE,

here we use "both sides detachment" for the detachment without inducing an X-point MARFE.

3. Neutral pressure for pumping from inside divertor slot

As show in Fig.2, the neutral pressures both at the inner private region, P_o^{in} , and at the outer private region, P_o^{out} , increase with an increase in n_e^{ave} during the detachment. Just before the appearance of the X-point MARFE, P_o^{in} rapidly decreases and becomes smaller than P_o^{out} . Therefore, the in/out asymmetry of the neutral pressure is reversed at the onset of an X-point MARFE. The rate of increase in P_o^{in} and P_o^{out} is much higher than that in n_e^{ave} during the divertor detachment. Thus, the neutral pressure in the private regions is a good measure for the onset of an X-point MARFE.

In Fig.3, P_o^{out} is plotted against P_o^{in} for several discharges similar to the shot in Fig.2. Crosses, open, and solid diamonds indicate inside detachment, both sides detachment and X-point MARFE, respectively. The thick curves show the temporal trajectory for each shot. Both sides detachment appears in the window in which increase in P_o^{out} dominates that in P_o^{in} . In this case, the pressure ratio P_o^{out} / P_o^{in} for the both sides detachment is between 0.6 to 0.8. It is suggested that if the pressure ratio is kept at 0.6-0.8, the both sides detachment could be sustained, and an appearance of X-point MARFE would be suppressed.

4. Neutral pressure for pumping from both side slots

The W-shaped divertor in JT-60U is modified to pumping from both (inside and outside) legs [5]. In this scheme, the separatrix can be located close to the dome, so that various combination of inside and outside gaps as well as X-point height is available. Here, the gap is defined as the distance between inside or outside strike point and the upper edge of inside or outside private dome. In the both-leg pumping case, the effective pumping speed at the exhaust slots is estimated by the pressure decay of filling neutral particles to be 25% higher than that in the inner-leg pumping case. Moreover, shielding effect of neutral particles at the divertor region is observed when the strike points are close to the exhaust slots (small gap).

The behaviour of divertor neutral pressure is plotted for the various gap and for the case with and without pumping. Figure 4 shows P_o^{out} plotted against P_o^{in} . The temporal evolution of P_o^{in} and P_o^{out} is similar to that in the previous pumping scheme from inside slot. That is, P_o^{in} increases more faster than P_o^{out} at the early phase of divertor detachment, in turn, P_o^{out} becomes larger at the later phase, and then X-point MARFE occurs. However, as clearly seen in the figure, detachment regime is wider with narrow gaps and pumping. The pressure ratio P_o^{out} / P_o^{in} , in which the divertor detachment appears, extends between 0.4 - 1.3, on the contrary to narrower region between 0.6 - 0.8 for the inside-leg pumping case.

5. Discussion

The result that the detachment regime becomes wider in the both legs pumping case, suggests again that the sustainment of divertor detachment could be achieved by use of the pressure ratio. The onset density of the X-point MARFE is 40-50% of Greenwald density. However, it is difficult to precisely suppress the X-point MARFE by the feedback control of line averaged density, since the transition from attachment to detachment and that from

detachment to X-point MARFE occurs at almost the same line averaged density as shown in Fig.2. In addition, onset density changes depending on the gap and X-point height.

Another possible method is to control by the divertor radiation [6,7]. During the divertor detachment close to an X-point MARFE, radiative region climbs up along the separatrix towards an X-point, so that feedback control with an actuator of the divertor radiation profile might be effective to sustain the divertor detachment. However, the dominant radiation in the divertor is from the impurity emission of carbon, so that an effect of the gas puff on the enhancement of carbon emission should be precisely examined. Moreover, the viewing chord of bolometer array should be carefully determined in order to estimate only the radiation in divertor region.

In contrast to the control by the divertor radiation, that by the neutral pressure deals the particles from gas puff, and is considered to be more direct and simple way. Therefore, feedback control of the inside/outside neutral pressure ratio is considered to good way to sustain divertor detachment, and now prepared for operation in JT-60U.

The mechanism of the change in asymmetry at the onset of the X-point MARFE is not clear yet. Possible mechanism might be the changes in in/out asymmetry of particle recycling and neutral pressure caused by the change of the ion flow in the scrape-off-layer [8] and/or the change in the regions of ionisation and recombination [9] at the onset of an X-point MARFE.

Further research is necessary to clarify the physics mechanism of the change in asymmetry.

Summary

The behaviour of neutral pressure at the onset of an X-point MARFE has been investigated using fast-response ionisation gauges. It is found that a rapid change in the in/out asymmetry in the neutral pressure at an onset of an X-point MARFE. The range of pressure ratio for the both sides detachment extends with narrow gaps with pumping from both legs.

The demonstration of feedback control with an actuator of the in/out pressure ratio in order to sustain the both sides detachment, and to avoid an appearance of X-point MARFE is planned in JT-60U.

References

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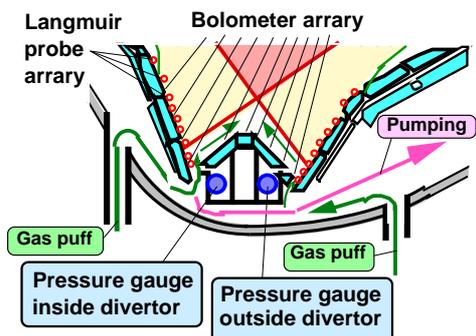


Fig.1 Location of fast-response ionisation gauges, line of sight of bolometer array and Langmuir probes for the divertor diagnostic.

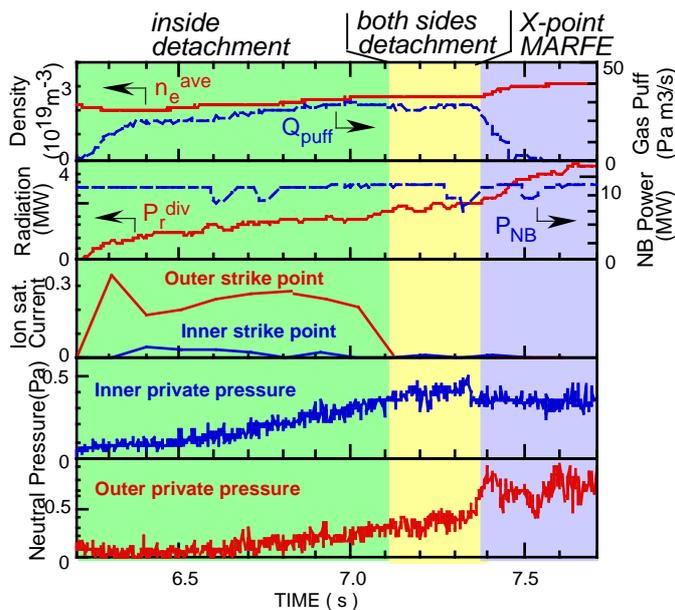


Fig.2 Temporal behaviour of typical plasma parameters during the divertor detachment and X-point MARFE.

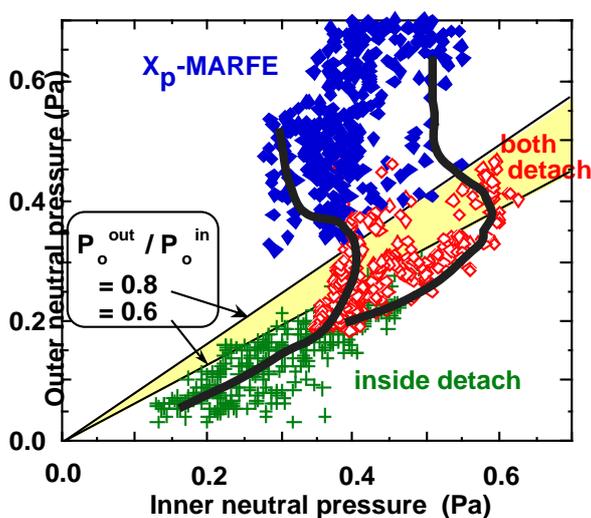


Fig.3 Neutral pressure at the outer private region plotted against that at the inner private region in the case of inside leg pumping.

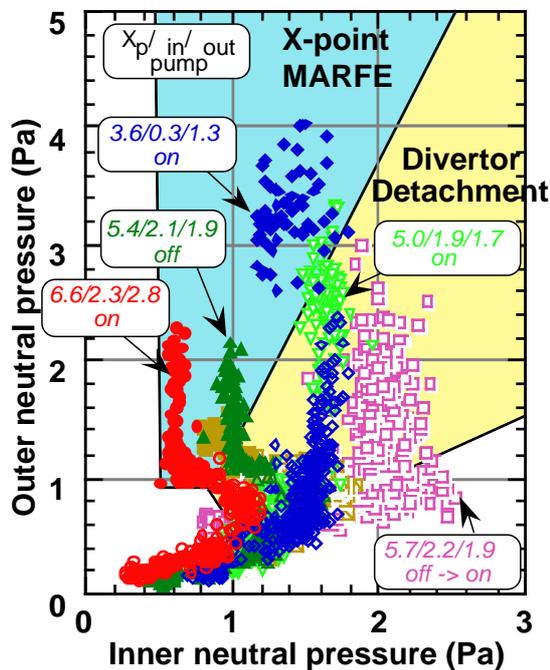


Fig.4 Neutral pressure at the outer private region plotted against that at the inner private region in the case of both legs pumping.