HEAT AND PARTICLE TRANSPORT OF SOL/DIVERTOR PLASMA IN THE W-SHAPED DIVERTOR ON JT-60U

N. Asakura, S. Sakurai, N. Hosogane, K. Itami, K. Shimizu, M. Shimada, A. Sakasai, Y. Koide, O. Naito, H. Tamai, S. Konoshima, H. Kubo, S. Higashijma, H. Takenaga, T. Sugie, H. Shirai, K. Masaki, T. Nakano and the JT-60 Team

Japan Atomic Energy Research Institute

Naka-mach, Naka-gun, Ibaraki-ken, 311-0193 Japan

Abstract

The plasma profile and parallel flow in the scrape-off layer (SOL) were systematically measured using Mach probes installed at the midplane and the divertor x-point. Quantitative evaluation of a parallel flow: naturally produced in a torus to keep the pressure constant along the field line, was consistent with the measurement. Geometry effects of the W-shaped divertor on the divertor plasma and particle recycling at the newly installed baffle plates were evaluated quantitatively using the edge plasma data.

1. INTRODUCTION

Formation of a detached divertor is essential in order to alleviate erosion of divertor plates during operation of a large, long-pulse tokamak such as ITER. The experimental database of SOL plasma profiles upstream from the divertor target is crucial for design of the divertor plate and baffles, and for clarifying the mechanisms of divertor plasma detachment and plasma flow. Capability for multi-point measurements of temperature and density distributions in the SOL, i.e. at the midplane, near the x-point and at the divertor plates, was developed in the W-shaped divertor on JT-60U (Fig.1). In particular, Mach probes were installed at the midplane and near the x-point in order to evaluate the parallel plasma flow. In this paper, studies of the SOL plasma transport along the magnetic field line, plasma flow, and comparison of the geometrical effects of the divertor (new W-shaped and previous open divertors) on the SOL plasma are summarized.

2. SOL PLASMA DISTRIBUTION ALONG FIELD LINE AND PLASMA DETACHMENT

The detached divertor was formed by deuterium gas puffing in L-mode discharges (I_p=1.1-1.7MA/B_t=3.5T/P_{NBI}=4.3MW). When the radiation loss in the divertor was increased, the divertor plasma started to detach from the target plate. Under the attached divertor condition of the W-shaped divertor, electron density near the strike point, n_e^{div}, was enhanced by a factor of two compared with that in the open divertor[1]. Figure 2(a) shows that the local electron temperature, T_e^{div}, decreases to less than 10 eV at the lower main plasma density, $\bar{n}_e$. These results indicate that the inclined divertor target and private dome are effective in condensing neutrals near the separatrix.

For the W-shaped divertor, the onset densities of the divertor detachment are decreased by 20% compared to those for the open divertor. When the divertor plasma starts to detach, electron temperature just below the x-point, T_e^{xp}, decreases to 10-20 eV due to an increase in radiation power near the x-point. The range of T_e^{xp} is consistent with an enhancement of radiation power by carbon ions (C^{3+}). The enhancement of carbon radiation near the x-point occurs at an onset of the x-point MARFE (~10% higher than the detachment onset $\bar{n}_e$) similarly in the open and W-shaped divertors. During the x-point MARFE, T_e^{xp} decreases to 3-5 eV near the separatrix, and the divertor plasma is detached below the x-point along the field line. Figure 2(b) shows that the degrees of the plasma detachment at the x-point and outer target, p_e^{xp}/p_e^{mid} and $2p_e^{div}/p_e^{mid}$, are ~0.1 and 0.02-0.04 for the W-shaped divertor, respectively. The value of $2p_e^{div}/p_e^{mid}$ is a factor of 8 as small as that for the open divertor. This may be caused by the high neutral density in the private region near the target[2].

Accompanied with the reduction in T_e^{xp}, a peak in the ion saturation current profile measured with the double probe facing the up-stream side, $j_{sat,up}^{xp}$, is enhanced near the separatrix [1, 3] as shown in Fig. 3(a). Local electron density, n_e^{xp}, is estimated to be ~1x10^{20} m^{-3}. At the same time, the ratio of the ion saturation currents at down- and up-steam sides, $j_{sat,down}^{xp}/j_{sat,up}^{xp}$, decreases (less than 0.1 near the separatrix), suggesting an increase in the parallel flow velocity to the divertor. During the x-point MARFE, $j_{sat,up}^{xp}$ near the separatrix decreases by one or two order of magnitude, and the large peak shifts to the boundary of the attached region. In the outer flux surfaces, T_e^{xp} profile becomes flat and n_e^{xp} increases. Radial diffusion of the particle flux is enhanced upstream.

The peaking of the local $j_{sat,up}^{xp}$ and, at the same time, a reduction in j_{sat}^{xp} ratio (from 0.1 to ~0.02) were generally observed only for the ion grad-B drift towards the divertor. One of the candidate mechanisms is a return ion flow caused by the poloidal ion drift, $V = (\boldsymbol{E} - p_i/en_i) \times \boldsymbol{B}/B^2$ (1), in the private region. Ion drift due to the radial electric field, E_r, and pressure gradient, p_i, is the same direction (from the outer target to the inner target though x-point), and V of 10-20km/s is estimated. The return ion flow may be driven along the field line to keep the pressure constant, and in particular large parallel ion flow is produced in the vicinity of the x-point, where the pitch of the field line is very small (0.01-0.02). In the detached divertor, the region of the large $j_{sat,up}^{xp}$ and very small j_{sat}^{xp} ratio shifts to the outer flux surfaces since the poloidal ion drift is associated with the large E_r and p_i. The radial shift of the poloidal ion drift can explain the change of the in-out asymmetry in the particle flux in the divertor, which was observed at the x-point MARFE occurrence[4].

3. REVERSAL OF SOL PLASMA FLOW WITH ION grad-B DRIFT DIRECTION

Control of the SOL plasma flow will be important from the view point of He exhaust, impurity shielding and reduction in the main plasma recycling. The SOL plasma flow in the direction of the magnetic field line is generally considered to be driven by the pressure difference from the stagnation point (such as the plasma top) to the divertor target. Experimental results, however, have shown the existence of the flow reversal at the main plasma edge for the case of the ion grad-B drift direction towards the divertor[5, 6]. The mechanism of driving the SOL flow should be investigated.

The parallel plasma flow was measured at the outer midplane in the L-mode plasma, and the direction of the plasma flow is estimated from the ratio of the ion saturation currents measured at down- and up-stream sides, $j_{sat,down}^{mid}/j_{sat,up}^{mid}$: a value larger than unity indicates a flow directed away from the divertor (i.e. "flow reversal"). The directions of the SOL plasma flow at the midplane and just below the x-point are shown in Fig. 4 for the ion grad-B drift towards and away from the divertor. For the ion grad-B drift away from the divertor (reversed B_t), $j_{sat,down}^{mid}/j_{sat,up}^{mid}$ at midplane and near the x-point are less than unity (except for the private region). The results show that the SOL plasma flows from the plasma top to the outer divertor target. On the other hand, for the ion grad-B drift direction towards the divertor (normal B_t), $j_{sat,down}^{mid}/j_{sat,up}^{mid}$ of more than 2 near the separatrix shows that the flow reversal occurs at the midplane, while the plasma flows from the x-point to the target plate in the divertor chamber.

The difference of the ion saturation currents is large at low $\bar{n}_e$, and $j_{sat,down}^{mid}/j_{sat,up}^{mid}$ becomes a unity at high $\bar{n}_e$ as shown in Fig. 5. Similar results have been obtained above the outer baffle plates in Alcator C-MOD[6], and they proposed a conventional mechanism: an increase in the local ionization in the outer divertor chamber caused by higher plasma temperature for the normal B_t direction. Since the plasma flow below the x-point directs to the target plate as shown in Fig. 4(b), the ion drift in the main plasma edge may play a role in driving the parallel flow rather than the increase in local ionization. One of the candidate mechanisms is the toroidal effect on the poloidal ion drift, which drives the parallel ion flux ("Pfirsh-Schlüter flow") at the midplane, $\Gamma_{//} \sim 2qn_i V \cos\theta$ (2) , where q is the safety factor, V poloidal ion drift velocity and $\theta = 0$ at the midplane. The idea was used to explain the DITE limiter result[7]. The flow direction is consistent with the measurements for three cases: (1) normal I_p and B_t directions, (2) reversal I_p and B_t directions, and (3) normal I_p and reversal B_t directions. The Mach number of 0.1-0.3 is comparable to that estimated from $j^{mid}_{sat,down}/j^{mid}_{sat,up}$ using the Hutchinson's formula [8]. Pumping from the inner exhaust slot influence neither the plasma flow velocity nor the direction. Pumping from the private region simultaneously at the inner and outer divertor chambers will be implemented for producing the plasma flow directed to the target.

4. SOL PLASMA FLOW IN ELMy H-MODE PLASMA

The SOL plasma flow in the improved core confinement plasma such as the ELMy H-mode is practically important for designing a reactor since it affects the efficiency of helium and impurity exhaust for reducing the dilution. The SOL plasma flow was measured by applying a constant voltage to the double probes with a sampling rate of 200 kHz. Figure 6(a) shows the time evolution of $j^{mid}_{sat,up}$ and the ratio of the ion saturation currents, where B_t = 2.1T and the frequency of ELM event was ~25 Hz. The values of $j^{mid}_{sat,down}/j^{mid}_{sat,up}$ decrease to less than unity just after every ELM event. Their radial profiles are plotted in Fig. 6(b). These results shows that the flow reversal exists between ELMs, and that it disappears in a short period of 1-2 ms. Rapid formation of the flow reversal at the end of the ELM pulse is one of the evidences that the drive mechanism exists in the plasma edge (i.e. may be caused by formation of large E_r and p_i).

5. RECYCLING AT THE BAFFLE PLATES

For the W-shaped divertor, the particle recycling above the baffle plates deduced from the Dα brightness profile was an order of magnitude larger than the calculation assuming only the back flow of neutrals from the divertor chamber [1]. The penetration probability of the baffle source neutrals into the core plasma is an order of magnitude larger than that of the divertor source. A reduction in the baffle source is required to decrease the neutral density in the main chamber, which may improve the energy confinement of ELMy H-mode plasma at high densities.

Quantitative analysis of generation mechanism of the baffle source was done with the 2-D Monte Carlo neutral transport code, introducing a recycling at the baffle plates using the measured SOL plasma profiles at the midplane and divertor plates. More than half of the local recycling flux above the baffle can be explained by an interaction of the expanded 2nd SOL plasma with a relatively long e-folding length of 6-8 cm. Fast ion flux due to the toroidal ripple loss is a candidate for the rest of the baffle source.

6. CONCLUSION

Formation of the divertor detachment and SOL plasma flow were experimentally investigated. Natural parallel SOL flow was measured at the SOL and divertor, which may be driven to keep the constant pressure along the field line. Quantitative evaluation of the drive mechanism at the main plasma SOL was consistent with the measurement.

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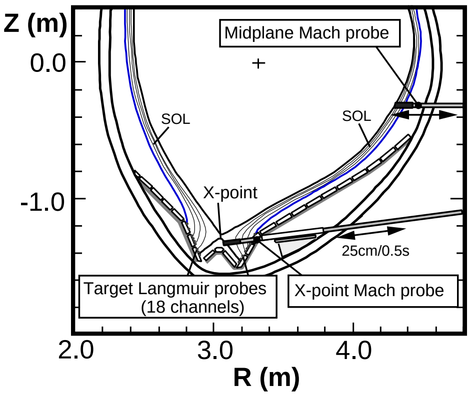

FIG. 1. Measurement of SOL plasma using Langmuir probes at midplane, near x-point and at divertor target.

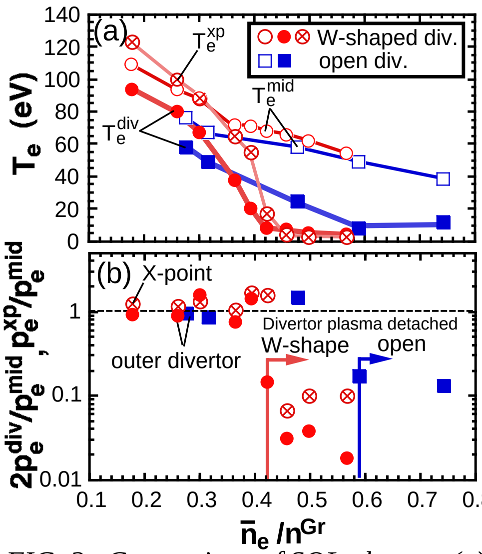

FIG. 2. Comparison of SOL plasma: (a) Te at midplane, near x-point and at outer divertor target, (b) electron pressure ratios as a function of main plasma density.

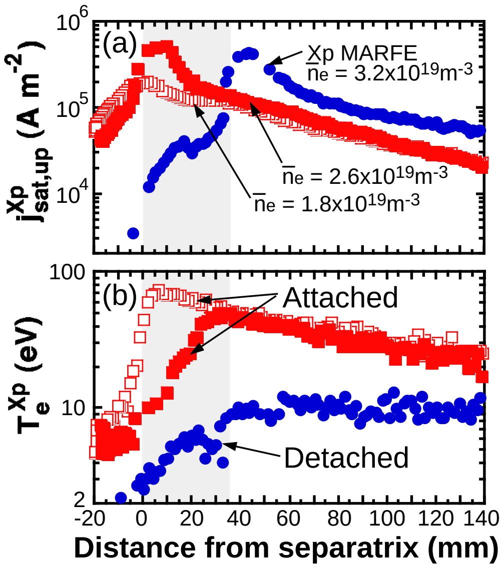

FIG. 3. Profiles of (a) jsat and (b) Te just below the x-point (measured with double probe facing x-point side).

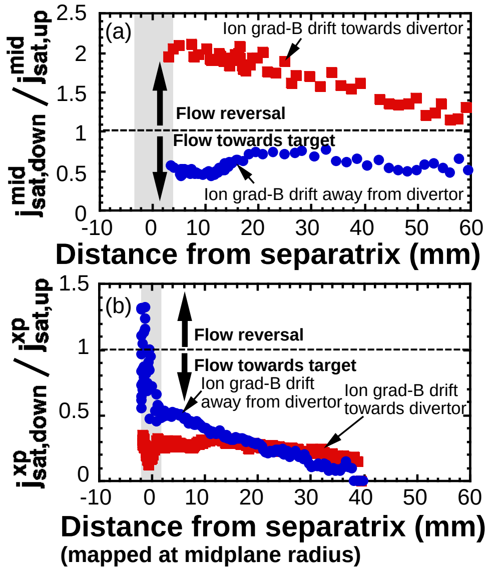

FIG. 4. Profiles of ion saturation current ratio measured (a) at midplane, (b) just below x-point. Squares and circles show the ion grad-B drift towards and away from divertor, respectively.

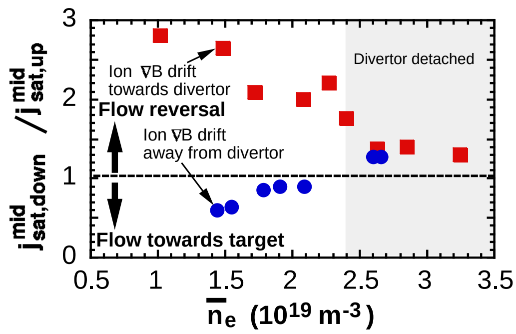

FIG. 5. Ion saturation current ratio near separatrix as a function of the main plasma density.

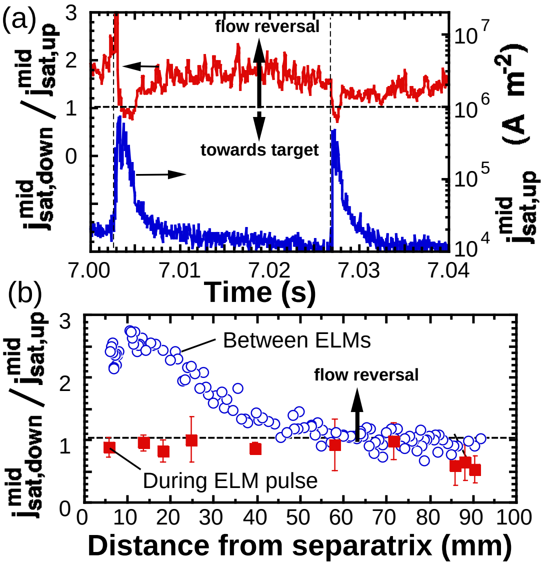

FIG. 6. Time evolution of (a) ion saturation current, and (b) the ion saturation current ratio in ELMy H-mode plasma.