High Mach Flow Associated with Plasma Detachment in JT-60U

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Recent new results of the high Mach flows associated with plasma detachment are presented on the basis of numerical simulations by a 2-D edge simulation code (the B2-Eirene code) and their comparisons with experiments in JT-60U W-shaped divertor plasma. High Mach flows appear near the ionization front away from the target plate. The plasma static pressure rapidly drops, while the total pressure is kept almost constant near the ionization front, because the ionization front near the X-point is clearly separated from the momentum loss region near the target plate. Redistribution from static to dynamic pressure without a large momentum loss is confirmed to be a possible mechanism of the high Mach flows. It has been also shown that the radial structure of the high Mach flow near the X point away from the target plate has a strong correlation with the DOD (Degree of Detachment) at the target plate. Also, we have made systematic analyses on the high Mach flows for both the "Open" geometry and the "W-shaped" geometry of JT-60U in order to clarify the geometric effects on the flows.

1. Introduction

To control plasma flows in the SOL and divertor region is one of the most important issues for the steady-state operation of the future fusion reactors. Plasma flows in the SOL and divertor region affect divertor performances in many aspects, such as, impurity shielding, helium exhaust, divertor in-out asymmetry, main plasma recycling, etc.

High parallel flows associated with plasma detachment have been observed in several tokamak experiments[1,2]. Large Mach flows up to Mach 1 or even larger have been measured near the X-point away from the target plate in these experiments. (Henceforth, abbreviation "**HMAD**" will be used for such high Mach flows in the detachment state.)

In Ref.[3], a 2D numerical study of HMAD by using the B2-Eirene code package[4-6] was done for the "Open" divertor geometry in JT-60U. To understand the physical mechanism of HMAD, detailed comparisons of the numerical results with those by a simple 1D analytic model were also made in Ref.[3]. Redistribution from static pressure to dynamic pressure without a large momentum loss has been shown to be a possible cause of HMAD observed in the numerical simulations. However, for the Open divertor geometry, flow measurements in the divertor region were not made. It was impossible to make the direct comparisons of the numerical results with the experimental results.

Recently, flow measurements with the fast movable Mach probe near the X-point have been made for the "W-shaped" divertor geometry in JT-60U[2]. To verify the physical mechanism discussed in Ref.[3] and to obtain more robust conclusions, comparisons with the experimental measurements are indispensable. In the present study, we have done the numerical calculations for the W-shaped geometry and their direct comparisons with the experimental results are made. In addition, geometric effects on HMAD are studied by comparing the numerical results for the W-shaped geometry with those for the Open geometry.

2. Numerical Model

Typical L-mode discharges for the Open divertor (Open-Div) and the W-shaped divertor (W-Div) geometry with similar main plasma parameters were chosen to evaluate the geometric effects on HMAD. Figure 1 shows the numerical grid near the divertor region for (a) the Open and (b) the W-shaped geometry. Bulk ion species D^+, all carbon impurity ion species C^+ - C^{6+}, and neutral species D, D_2, C are considered in the analysis. At the core interface boundary, i.e., at the innermost flux surface of the grid inside the separatrix in Fig.1, the bulk ion density n_D and the total input power P_{in} are specified. For the boundary conditions of the target plate, the usual Bohm condition is used. The remaining simulation models/conditions, such as transport model, are almost the same as those in Ref.[3]. To simulate the attached state and the detached state, n_D has been changed for each numerical run, while the remaining conditions are kept fixed.

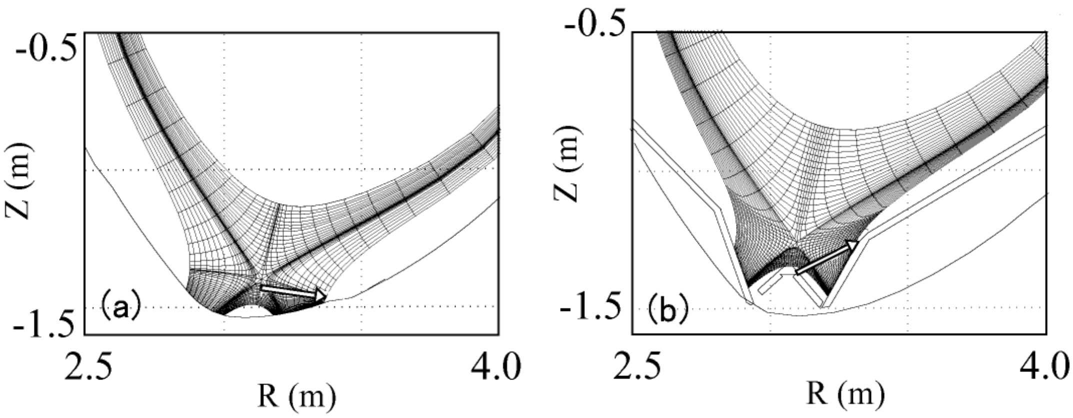
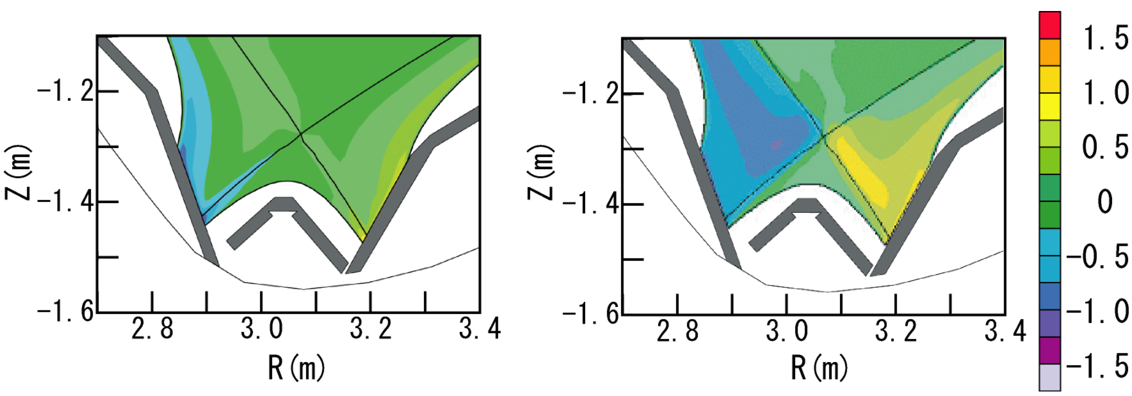


Fig.1 Numerical grid near the X point in the divertor region:
(a) Open divertor geometry (Open-Div) and (b)W-shaped divertor geometry (W-Div).

3. HMAD in the W-shaped Divertor Geometry and Its Physical Mechanism

Figure 2 shows 2D spatial profiles of the parallel flow velocity $u_{//}$ for D^+ near the X-point in the W-shaped divertor. The spatial profiles are compared between (a) the attached plasma case (n_D=1.0×10^{19} m^{-3}) and (b) the detached plasma case (n_D=2.0×10^{19} m^{-3}). The total input power (P_{in}=2.5 MW) is the same for both cases. The flow velocity is shown as the local Mach number ($M \equiv u_{//} / C_s$), i.e., $u_{//}$ is normalized by the local isothermal sound speed C_s. In Fig.2, the positive direction of the velocity is defined as the direction from the inner divertor plate to the outer divertor plate in the edge plasma region. Thus, the negative sign means the flow is directed towards the inner target plate, while the positive sign means it is directed towards the outer plate.

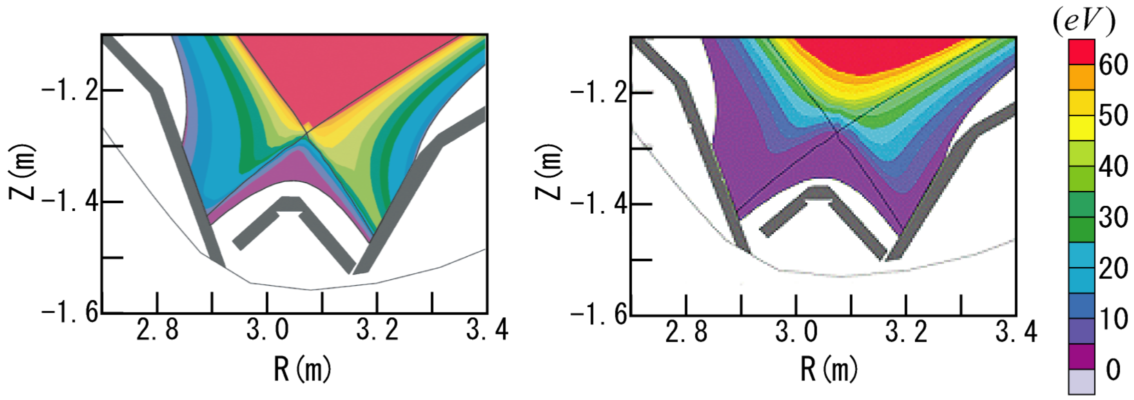


(a) attached state *(b) detached state*

Fig.2 2D spatial profiles of parallel Mach number in the divertor region for the W-Div.

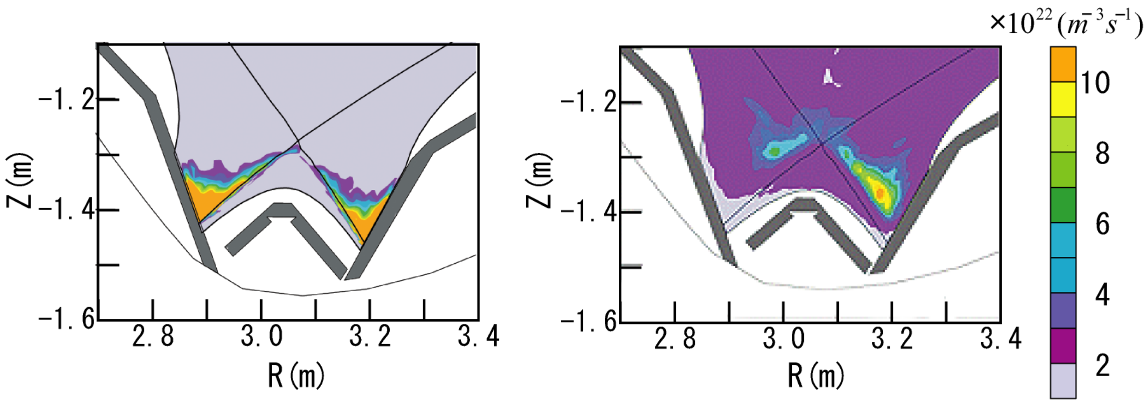
In the attached plasma case, the Mach number in the bulk of divertor region is still low as shown in Fig.2(a). The Mach number reaches M~1 only near the target plate. On the other hand, in the detached plasma case, high Mach flows appear near the X-point away from the target plate.

To understand the formation mechanism of HMAD in Fig.2(b), basic divertor characteristics are compared between (a) the attached state and (b) the detached state in Fig.3-Fig.5. Typical 2D profiles of T_e and ionization source S_i (D^+ions/m^3/s) are shown, respectively, in Fig.3 and Fig.4.



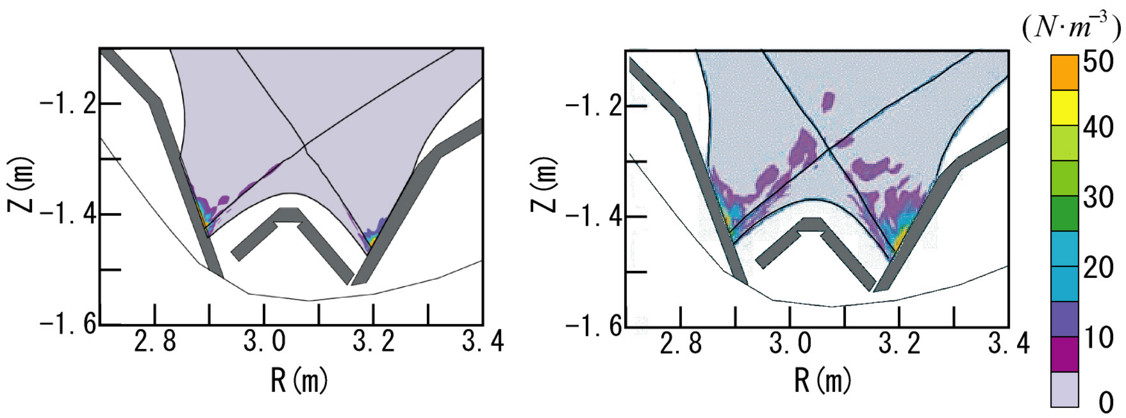
(a) attached state *(b) detached state*

Fig.3 2D profiles of electron temperature T_e in the divertor region for the W-Div.



(a) attached state *(b) detached state*

Fig.4 2D profiles of the ionization source density S_i in the divertor region for the W-Div.



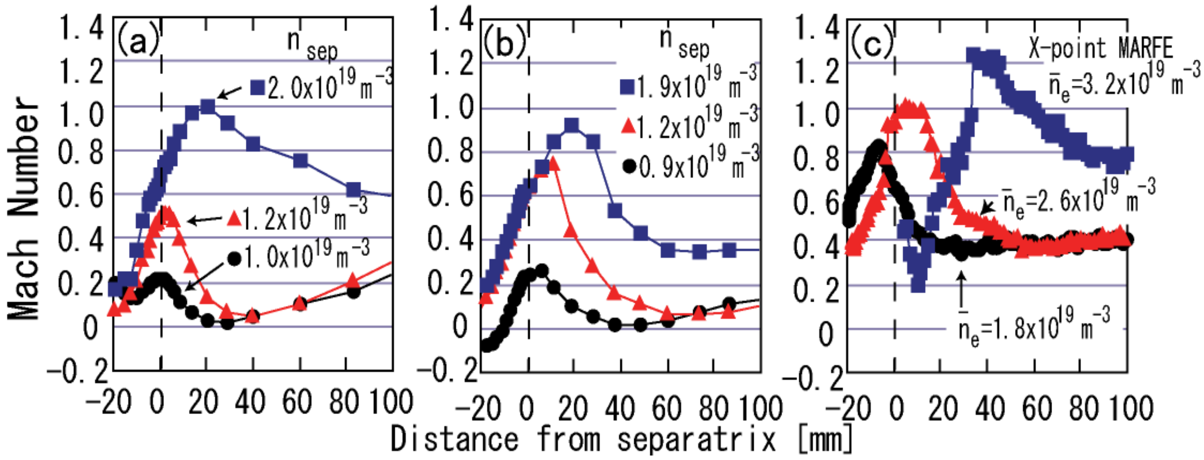
(a) attached state *(b) detached state*

Fig.5 2D profiles of the momentum loss density S_m in the divertor region for the W-Div.

In the attached case, T_e is still high in the divertor region and S_i is localized near the target plate. On the other hand, in the detached case, T_e drops rapidly towards the target plate and becomes T_e<5eV in front of the target plate. Due to this large decrease in T_e, the ionization front moves away from the target plate as shown in Fig.4(b). The HMAD region in Fig.2(b) is almost coincident with the ionization region in Fig.4(b) where the static pressure drops strongly due to the large decrease in T_e. Figure 5 shows 2D profiles of the momentum loss S_m (N/m^3) for D^+ ion fluid due to the interaction with neutrals, e.g., CX-collision. In the detached case, it should be noted that the region where S_m is large in Fig.5(b) is almost separated from the ionization region in Fig.4(b). As a result, the total pressure is kept almost constant along the field line near the ionization region away from the target. Thus, the pressure gradient force due to the large drop of the static pressure possibly drives HMAD near the ionization front, i.e., redistribution from static pressure into dynamic pressure is a possible cause of HMAD observed in the simulation.

4. Comparison with Experiments and Effect of Divertor Geometry on HMAD

The radial profiles of the parallel Mach number are shown, respectively, in Fig.6 (a) for the Open-Div and Fig.6(b) for the W-Div. The *M*-profiles are plotted along the path shown in Fig.1(a) and (b) by arrows. The following interesting common features can be seen; 1) as the separatrix electron density n_{sep} at the mid-plane increases, the Mach number becomes larger, 2) the Mach number first starts increasing near the separatrix and then the peak moves radially outward, and finally, 3) the peak value becomes quite large ($M \sim 1$). In the W-shaped geometry, the radial profiles of the parallel flow were measured by the fast movable Mach probe near the X point[2]. The measurements were done along almost the same path in the numerical simulation. The experimental results are shown in Fig.6(c) for each line average density $\overline{n}_e$ of the main plasma. The Mach number is estimated from the probe data by using the Hutchinson's formula[8].

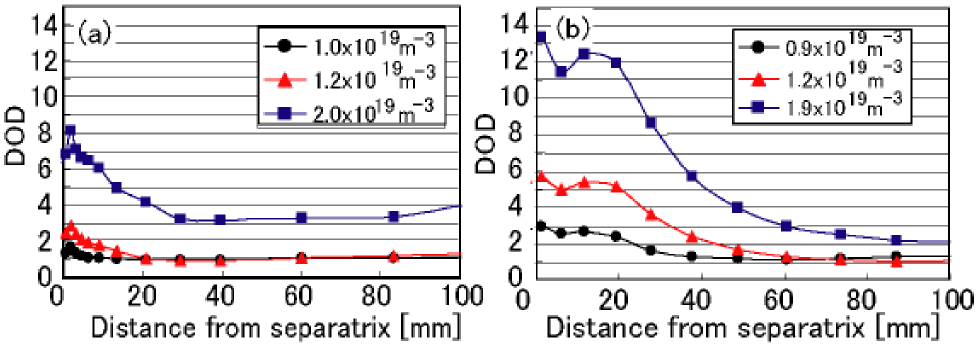


(a)Open-Div (numerical result)   (b)W-Div(numerical result)   (c) W-Div (Experimental result)
Fig.6 Radial profiles of the Mach number near the X-point in the outer divertor region.

The qualitative features obtained in the numerical simulation, i.e., 1), 2) and 3) described above, agree well with the experimental results in Fig.6(c). For the largest $\overline{n}_e$ in Fig.6(c), the impurity radiation near the X point is enhanced (X-point MARFE) and the detachment region is extended more radially outward from the separatrix in comparison with the case of $\overline{n}_e = 2.6 \times 10^{19} m^{-3}$. Also in the simulation, X-point MARFE appears for a larger n_{sep} than in Fig.6(b) and the peak of the *M*-profile moves further outward and the peak value becomes larger.

The radial *M*-profiles for the Open-Div and the W-Div in Fig.6(a) and Fig.6(b) have a close relation to the detachment characteristics. To make a discussion more quantitative, Fig.7 compares the radial profiles of the DOD [7] at the target plate. The DOD value at each point on the target plate is mapped to the upstream point in Fig.1 where the radial *M*-profile is plotted. The DOD is a figure of merit for the particle flux detachment. The DOD

$(\equiv Cn_{sep}^2/\Gamma_d)$ is defined by the ratio of the particle flux in the attached state, which scales as Cn_{sep}^2 (C is a proportional constant), to the particle flux Γ_d in the detached state. Thus, if the DOD becomes larger than unity, then the detachment starts. The value larger, the detachment becomes deeper. At the low and the medium n_{sep}, the plasma is still attached besides the region very close to the separatrix for the Open-Div, while the detachment has already started in relatively wide region for the W-Div. However, at the highest density case, the DOD profile is more peaked for the W-Div. The radial extent of the high Mach flow with M~1 for the W-Div is also more peaked than that for the Open-Div as shown in Fig.6 (a) and (b). In the Open-Div without the baffle plate and the doom structure, recycling neutrals are relatively free and tend to spread out radially. The DOD values for the Open-Div near the separatrix become smaller than those for the W-Div, while they become larger at the outer part of the target plate. As a result, the DOD profile becomes broader for the Open-Div.



(a) Open-Div *(b) W-Div*

Fig.7 Radial profiles of the DOD (Degree of Detachment) at the outer target plate.

5. Conclusions and Future Study

In the numerical simulations for the W-shaped divertor geometry, HMAD appears near the ionization front away from the target plate, where T_e rapidly drops, as in Ref.[3] for the Open divertor geometry. Direct comparisons with the experiments in the present study strongly support our explanation for the formation mechanism of HMAD proposed in Ref.[3]. In addition, by comparing the radial profiles of DOD at the target plate with those of the Mach number away from the target plate, it is shown that the radial profile of HMAD has a strong correlation with the DOD at the target plate.

However, in the experiments, relatively large Mach flows have been observed even in the attached state. The cause of such relatively high Mach flows in the attached state has not been clearly understood yet. One of the possible causes is effect of various kinds of drift in the SOL and divertor region. These effects are not taken into account the present analysis. In the future, these effects will be taken into the analysis.

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