Effects of divertor baffling on SOL plasma during the high power operation

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The steady-state operation of next-step fusion devices requires both the deposited heat flux density on the divertor target below 10 MW/m^2 and plasma temperature at the target below 5 eV to ensure adequate lifetime. Therefore, it will be essential to achieve highly dissipative or detached divertor conditions for the control of heat flux and erosion in a fusion reactor. One of the most effective methods to promote the achievement of detachment is to improve neutral trapping and impurity screening in the divertor by changing the divertor structure [1]. Previous experiment and modeling works on JET, DIII-D, C-mod and JT-60U studies highlight the importance of the divertor target shape and baffling on the plasma detachment [2–5]. However, the impact of the divertor baffling on the SOL plasma is still unclear, which may have a great impact on the long pulse steady state operation. This question should be answered during the physical design of the lower divertor of the Experimental Advanced Superconducting Tokamak (EAST). We aim to answer this question by using the numerical simulations in the present work.

In this work, a lower single null (LSN) magnetic field configuration is used with normal B_t direction (the direction of $B\times\nabla B$ points to the lower divertor). The baffle structures of the two divertors both having a horizontal target, one completely open and the other tightly closed are applied. By using this specific baffling for 'closed divertor', (1) the meshes for the two cases are almost identical with the only difference being the baffling, (2) the most closed baffling can be obtained without changing the mesh. This enables direct assessment of the effect of divertor closure on detachment, without dealing with the complications of different plasma solutions caused by different meshes. Electrons and ions (D and C) of each ionization state are handled by the B2.5 code [6], while the neutrals (D, C and D_2) are tracked by the EIRENE code [7], where ionization, charge exchange, dissociation, elastic collisions and volume recombination processes are taken into account.

Increasing the closure of the divertor is potentially an effective way to achieve detachment at lower upstream. Experimental studies of divertor closure on the divertor solutions in DIII-D and JET indicate that the divertor closure has a great impact on the onset of divertor detachment and pedestal plasma. Two cases are simulated with the identical input parameters but different neutral baffling to crease an open and a closed divertor, which are the same to the previous work [2]. The peak target plasma parameters as functions of separatrix electron density at OMP show that the closed structure enables the divertor plasma to enter into highly dissipative and detached divertor conditions at a significantly lower upstream density, which is illustrated in Fig. 1(b) and has been explained in detail in Ref. [2].

To evaluate the effects of divertor closure on the SOL plasma, the open and closed are compared with the identical input upstream density, i.e. the D^+ density at the core-edge interface (CEI) is fixed to $n_{D+}^{CEI} = 2.0\times10^{19}\ m^{-3}$. The corresponding divertor plasma parameters cross-target are shown in Fig. 2. It can be seen that the closed divertor has much lower T_e and power heat load on the target, and higher electron density, neutral density and ion flux. For the open divertor the peak T_e is about 56 eV, and the peak T_e of the closed divertor is below 5 eV, which means that the open divertor is in the attached regime and closed divertor is almost in detached regime. Therefore, the closed divertor can enable the achievement of the detachment at a much lower upstream density. This indicates that the divertor closure may have big impact on the SOL plasma.

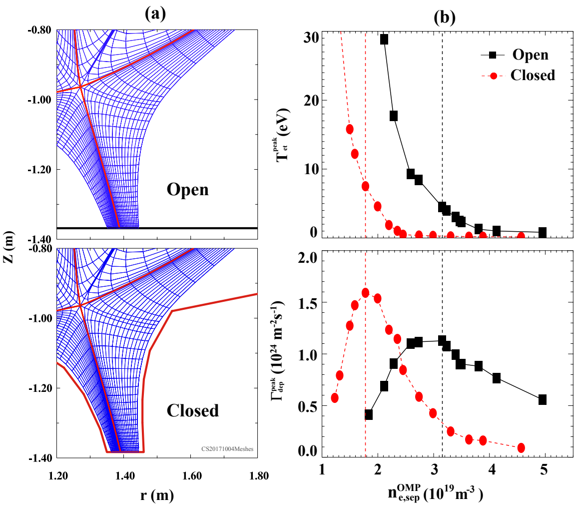

Figure 1 (a) Sketch of the simulation meshes and the wall structures for no baffle (completely open) and baffle (tightly closed) divertor cases; (b) Density scan: peak values of T_{et}^{peak} and Γ_{et}^{peak}, at the outer target, as functions of the upstream density $n_{e,sep}^{OMP}$, for both open and closed divertor cases.

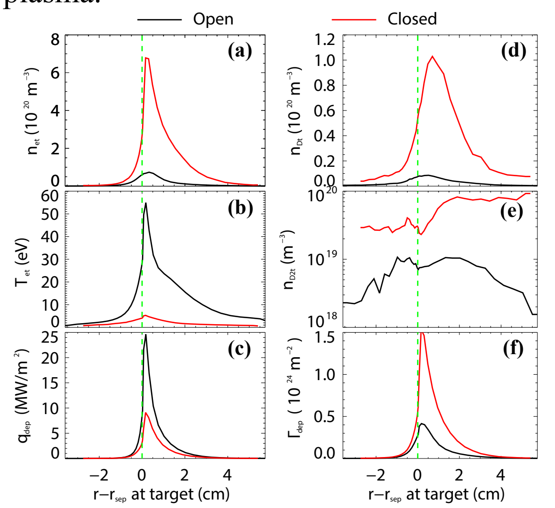

Figure 2 For the identical input core-edge interface (CEI) density $n_{D+}^{CEI} = 2.5{\times}10^{19}\, m^{-3}$, cross-target profiles of n_{et}, T_{et}, deposited heat flux density q_{dep}, the atomic D density n_D, molecular D_2 density n_{D2} and the deposited particle flux density Γ_{dep}, along the outer divertor target for both open and closed divertor cases. The subscript 't' indicates the target.

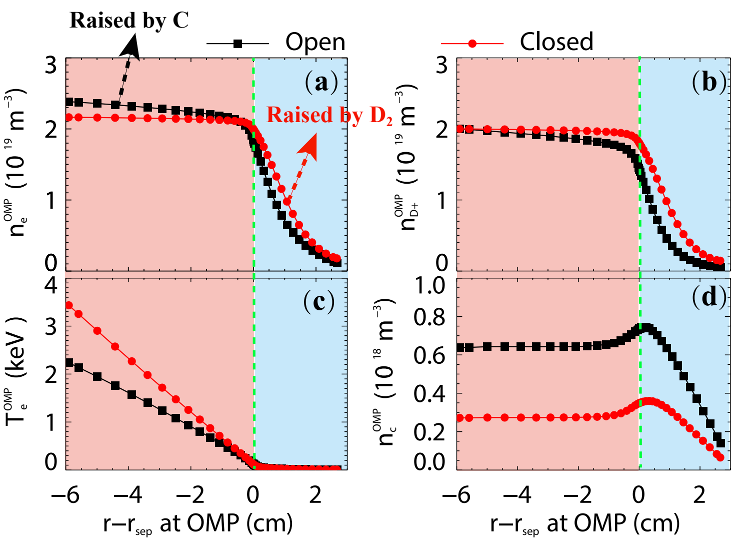

Figure 3 For the identical input CEI density $n_{D+}^{CEI} = 2.0{\times}10^{19}\, m^{-3}$, radial profiles of electron density n_e, electron temperature T_e, D^+ density n_{D+} and total carbon impurity density n_C at the OMP for both open and closed divertor cases.

To check the effect of the divertor closure on the SOL plasma, the profiles of n_e, n_{D+}, T_e and n_C at OMP are shown in Fig. 3 for both open and closed divertor cases. The core density boundary condition is fixed to $n_{D+}^{CEI} = 2.0{\times}10^{19}\, m^{-3}$. By comparing the electron density n_e, we can see that the n_e of closed divertor outside the separatrix is higher and inside the separatrix is lower than that of the open divertor. For the D^+ ion density, it illustrates that the closed divertor has significant higher n_{D+} outside the separatrix than that of the open divertor, indicating that the closed divertor has great impact on the SOL and pedestal plasma. For the total carbon impurities n_C, the simulation results show that the open divertor has much higher Carbon impurities density than the closed divertor. Both the n_{D+} and n_C can explain the reason of the difference of n_e profiles between open and closed divertors. The higher n_e at SOL of the closed divertor is raised by the neutral D_2 and D, which are dissociated and ionized to D^+;

the higher n_C inside the separatrix of the open divertor case is induced by the carbon impurities. The ionization of D and C can significantly increase the electron density. In the present case, the power across the CEI is fixed to P_{SOL} = 3MW, which is the product of the particle flux and temperature. The particle flux across the CEI depends on the gradient of the electron density. The open divertor has deeper n_e gradient at the CEI, thus, larger particle flux. Therefore, T_e of the open divertor at CEI is lower than that of the closed divertor as shown in Fig. 3(c). From Fig. 3 we can deduce that the closing the divertor could prevent C impurities from escaping the divertor, thus decrease the core plasma density and increase the core T_e; moreover, it can also increase the pedestal density and pressure, thus, increase the core-edge compatibility.

The D core fuelling was modestly lower in the closed divertor configuration observed in DIII-D experiment [8], which is in agreement with our simulation (Fig. 3(b)). UEDGE simulations indicate that the decrease in both D core fueling and core carbon density with the closed divertor compared to the open divertor configuration is due to greater divertor screening of neutrals [9].

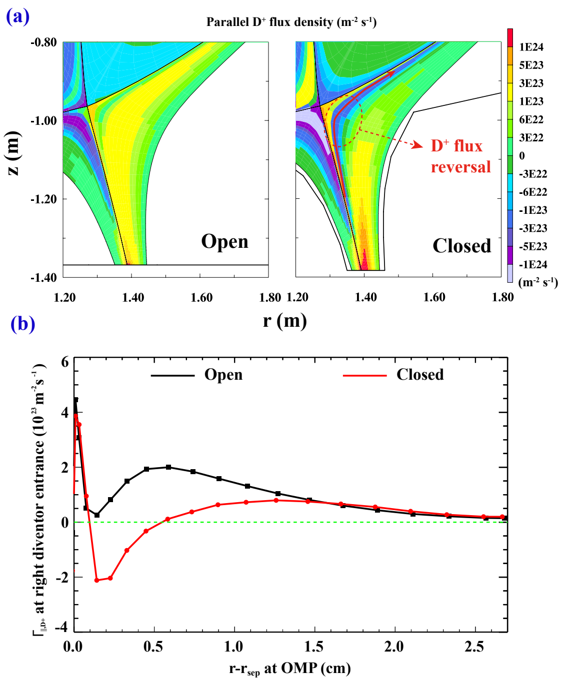

Figure 4 (a) The contour of parallel D^+ flux density, **(b)** the profiles of parallel D^+ flux density at OMP, for both open and closed divertor cases. The direction: positive means direction from inner target to outer target, negative means direction from outer target to inner target.

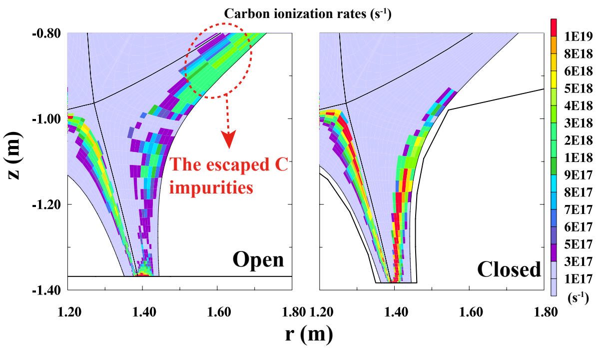

Figure 5 Contour of carbon ionization rate of both open and closed divertor cases.

To explain the impact of the divertor closure on the upstream SOL plasma as indicated in Fig. 3(b), the parallel D+ flux density of both open and closed divertor cases are shown in Fig. 4. It can be seen from the contour distribution (Fig.4(a)) that there is a significant D^+ flux reversal region near the separatrix of the closed divertor case, whereas, the D^+ flux reversal does not appear in the open divertor. The reason may be that the closed divertor reaches almost detachment ($T_e < 5$ eV), and the open divertor is still in the attached regime. To make it clearly, the profiles of parallel D^+ flux at the OMP in the radial direction is shown in Fig. 4(b). It illustrates that in the far SOL region, no significant difference of parallel D^+ flux between closed and open divertor is observed; whereas, in the near separatrix flux tubes (~0.5 cm) significant differences are found, especially the flux reversal occurs in the closed divertor. The reversal of the parallel D^+ flux is the reason of the n_{D+} enhancement in the SOL region for closed divertor.

The accumulation of neutral ionization towards the separatrix tends to create a region of deuterium flow reversal in this area. Flow reversal occurs in a flux tube when the ionization source exceeds the ion loss to the divertor target for that flux tube. As a consequence, the deuterium ion flow is directed away from the divertor in an extended region, which starts at some distance from the target. The reversed flow is mainly driven by the divertor ionization balance and not by SOL drifts [1]. A region of reversed flow close to the separatrix is found for both divertors which extends beyond the divertor entrance.

The contours of carbon impurity ionization rates distributions in both open and closed divertor are shown in Fig. 5. It can be seen that the highest ionization rate region locates near the strike point, mainly due to the highest impurity produced by the peak incident particle flux. The ionization region of the closed divertor mainly distributes inside the divertor region of the closed one; whereas there is remarkable C ionization region in the upstream of open case. This indicates that the closed divertor could help to prevent C impurity from escaping the divertor region, and the impurity of the open divertor can easily transport to the upstream region. This can explain why the n_c at OMP of the closed divertor is much lower than that of the open divertor as shown in Fig. 3(d). The reason can be attributed that when the C impurity hit the wall, it can be totally absorbed; therefore, the additional baffle of the closed divertor can significantly reduce the C from escaping the divertor plasma region via vacuum (the space between the plasma and wall). For the open divertor, the produced C impurity can run out of the divertor plasma region and enter to the vacuum, and then transport back to the upstream plasma region; therefore, the other C ionization region appear outside of the open divertor. Some reduction in the carbon impurity concentration has been observed with the more closed W-shape divertor [1]. It has been pointed out by the JET experiments that a closed divertor reduces intrinsic impurity content in non-ELMing discharges [10,11]. These are in agreement with our simulation results.

In this work, by comparing the closed and open divertor using SOLPS simulation, it is found that the divertor baffling has a great impact not only on the divertor plasma but also on SOL plasma, mainly due to the particle flux reversal and divertor shadowing of the carbon impurity.

Acknowledgements

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