

Study of the divertor pumping capability in V-Shaped JT-60SA divertor

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Introduction

The main mission of the JT-60SA project is to support and complement the ITER experiment to address key physics and technology aspects in view of future commercial fusion reactors[1,2]. The development of integrated scenarios is a major concern to maintain the desired plasma performance while also achieving a detached plasma at the targets, characterized by heat fluxes and plasma temperature below the allowable technological limits. In the second phase, the transition to a full W-metal wall is foreseen. Therefore, integrated power and particle exhaust scenarios represent a key element in operating the machine in safe conditions, thereby limiting the wall sputtering and, in turn, the subsequent core plasma contamination by high-Z impurities. An optimized divertor geometry is adopted in the outer divertor, featured by a V-shaped divertor corner[3], designed to enhance the divertor detachment at low mid-plane density. In this contribution, we present the study of the effect of the divertor geometry on the divertor and sub-divertor conditions. In particular, we aim to analyse the impact of the V-shaped geometry on the pumping capability of the system. In addition, we also discuss the impact on the detachment achievement and the neutral compression in the divertor.

Radiative cooling Ne seeded scenario

Table 1: Parameters of the JT-60SA Scenario #2[1].

R	a	B _t	I _p	κ	<n _e > _{line}	P _{aux}	P _{in,ρ=0.9}	Γ _{D+,core}	λ _q
(m)	(m)	(T)	(MA)	-	10 ¹⁹ m ⁻³	MW	MW	(10 ²¹ D/s)	mm
2.96	1.18	2.25	5.5	1.87	6.3	41	20-30	1.88	1.5

The edge transport code suite SOLPS-ITER[4] has been used to simulate the high-performance full-current Single Null scenario (scenario #2[1]) of JT-60SA equipped with a full metal wall. The parameters characterizing the scenario are given in Table 1. It represents the most demanding scenario from the power exhaust viewpoint due to the high level of P_{aux} and low outer midplane (OMP) separatrix density, n_{esep,OMP} = 2x10¹⁹ m⁻³. The power input set in the simulations is imposed at the core boundary, P at ρ=0.9. A scan in P_{in,ρ=0.9} is performed between 20 and 30 MW due to the large uncertainty on the core radiation and ELM-related diamagnetic energy change. A radiative cooling scenario is simulated by considering Ne seeding to obtain acceptable plasma divertor conditions.

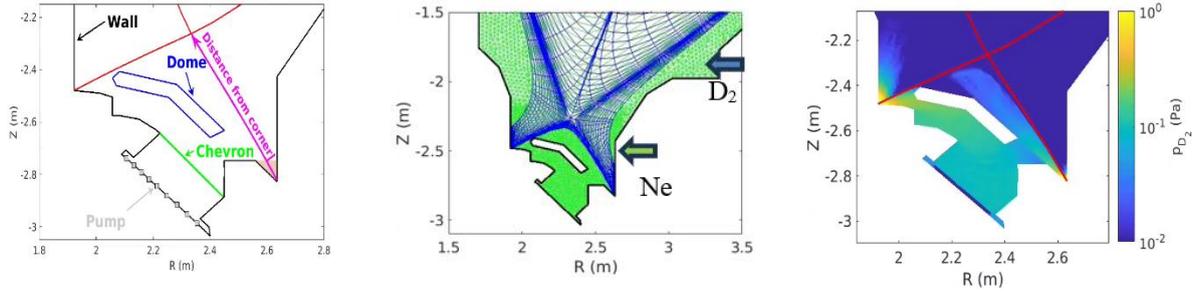


Figure 1: On the left, the schematic view of the wall geometry in the divertor and sub-divertor region. The chevron is in green and the pump locations in gray. Also shown is the distance from the corner entrance reference frame in magenta. The corner area is highlighted with a shaded area. In the center, the mesh used for the calculations. In blue the mesh for the plasma solver, and in green the triangular mesh for the neutral description. The locations of the gas puff for D_2 and Ne are shown. On the right, the D_2 neutral pressure in the divertor and sub-divertor region for the case with $n_{\text{sep,OMP}} = 2 \times 10^{19} \text{ m}^{-3}$ and $P_{\text{in},\rho=0.9} = 26 \text{ MW}$.

Figure 1 shows the geometry adopted in the calculations. The neutral simulation domain, the green triangles, extends up to the actual cryopump position. A semi-transparent surface with a transparency $R_t=0.5$, the so-called chevron, is used in the calculation to mimic the presence of obstacles to the neutral flow towards the sub-divertor. An albedo coefficient of the pump is set to $\alpha=0.95$, corresponding to a pumping speed $S=100 \text{ m}^3/\text{s}$. The main D_2 gas is puffed through the outer lower supply line, while the Ne gas is at the outer divertor. The separatrix density is feedback controlled by Γ_{D_2} to get the desired $n_{\text{sep,OMP}}$ value. The external Ne gas puff is adjusted to achieve a partial detachment plasma condition at the outer divertor target. The transport parameters used were derived from actual JET discharges and rescaled according to Eich's scaling [5], according to the methodology presented in [6]. In the $P_{\text{in},\rho=0.9}$ scan, $f_{\text{rad}} > 80\%$ is necessary to detach the plasma close to the outer strike point, i.e. in the region of high ion fluxes. The higher the input power, the higher the Ne seeding and the corresponding core plasma contamination. The maximum power carried by charged particles is of the order of $P_{\text{max,wall}} = 4\text{-}6 \text{ MW}$. The V-shaped corner favours the detachment of the plasma in the strike point region by trapping neutral particles, thus enhancing the momentum loss. However, neutral D_2 molecules are not able to reach the sub-divertor and the pump location. This behaviour is shown in Figure 1, for $P_{\text{in},\rho=0.9} = 26 \text{ MW}$. The D_2 neutral pressure is higher in the outer divertor corner while it tends to strongly decrease at the pump location, $p_{D_2,\text{sub-divertor}} \approx 0.1\text{-}0.2 \text{ Pa}$. The pumping rate is drastically reduced to $\Gamma_{D_2,\text{pump}} = 2.1 \times 10^{21} \text{ D/s}$, similar to the $\Gamma_{D^+,\text{core}}$ injected by the NBI.

Effect of V-shaped geometry on pumping

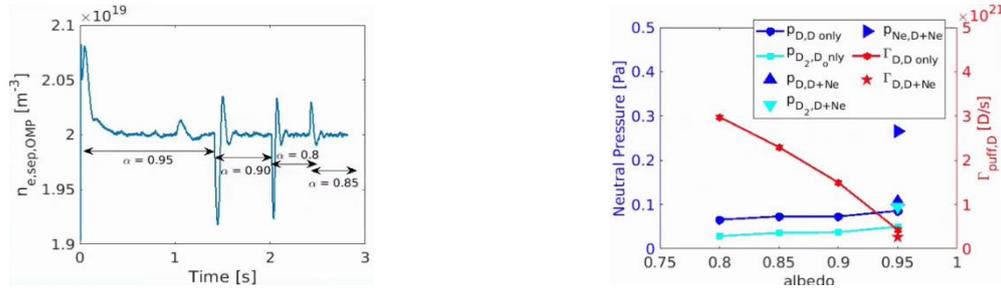


Figure 2: On the left, the time trace of $n_{\text{sep,OMP}}$ for the different values of α . On the right, the sub-divertor neutral pressure in front of the pump and the gas throughput as a function of α . $P_{\text{in},\rho=0.9} = 10 \text{ MW}$ is set in the simulations.

The effect of the V-shaped corner on the pumping properties of the system is studied in a simplified case: a pure D plasma with a reduced $P_{\text{in},\rho=0.9}$ level and fixed $n_{\text{sep,OMP}} = 2 \times 10^{19} \text{ m}^{-3}$.

A sensitivity study has been carried out to investigate the effect of the albedo α on the pumping rate and sub-divertor neutral pressure. The time trace of the upstream density is shown in Figure 2. The strong changes in $n_{\text{sep,OMP}}$ are related to a change in α (also indicated in the plot), while the feedback scheme can recover the density target value in $\Delta t \approx 200 \text{ ms}$. An

attached plasma condition is obtained at the outer target. The pressure in front of the pump is quite low, $p_{D/D2} < 0.1$ Pa. The puffing rate Γ_{D2} decreases linearly with α , hence confirming the negligible effect of α on the neutral in the sub-divertor with similar divertor and outer midplane plasma conditions. It is worth noting that similar neutral pressures $p_{D/D2}$ are obtained in the Ne case in similar outer divertor target conditions. This validates the adoption of a simplified pure D case to study the D pumping behaviour.

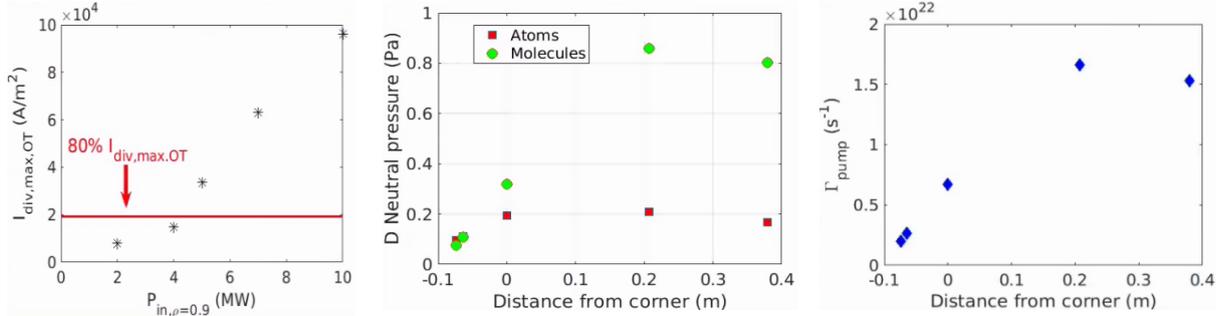


Figure 3: On the left, the current density peak on outer target $I_{div,max,OT}$ as a function of $P_{in,\rho=0.9}$. The red line indicates a reduction of $I_{div,max,OT}$ by 80%. Neutral pressure (atomic in red and molecular in green) in front of the pump in the center and pumped flux Γ_{pump} on the right for different positions of the ionization front.

To quantify the effect of the V-shaped geometry, a scan in $P_{in,\rho=0.9}$ has been performed. The change in the input power allows us to cope with a wide range of plasma conditions and assess the effect on the pumping capability. Figure 3 shows the results obtained in the power density scan with a fixed low mid plane density, $n_{sep,OMP} = 2 \times 10^{19} \text{ m}^{-3}$. The peak current density along the target is shown on the left. In attached plasma conditions, $P_{in,\rho=0.9} = 7$ and 10 MW, the neutrals are completely trapped in the corner. The plasma starts to detach ($T_{e,OT} < 5$ eV) in the strike point region at $P_{in,\rho=0.9} = 5$ MW, while for the last two points in the scan ($P_{in,\rho=0.9} = 2$ and 4 MW) the plasma is completely detached and the $I_{div,max,OT}$ drop by 80%. The D ionization front tends to move away from the target. When the plasma starts to detach, a path for the molecules towards the sub-divertor region opens: the neutral molecules can be leaked, and the corresponding neutral pressure in front of the pump increases. To quantify the effect of the geometry, we define the position of the ionization front along the outer separatrix leg by considering the fraction of the ionizations over the total ionized particles in the outer divertor chamber [8]. The distance from the target is measured by considering the entrance into the corner as the reference, as shown in Figure 1 (magenta axis along outer divertor leg): positive values are located above the corner, while negative ones are inside the shaded area, identifying the corner. Figure 3 shows that a first increase in the $p_{D2,sub-divertor}$ is observed when the ionization front is at the corner entrance (distance from the corner equal to zero). The stronger the detachment, the closer the ionization front to the X-point. As a result, the neutral trapping into the corner is less effective, leading to $p_{D2,sub-divertor} \approx 1$ Pa. The same trend is observed for the pumping rates, with $\Gamma_{pump} \approx 1.5 \times 10^{22}$ D/s in deep detached plasma conditions.

Effect of a change in the divertor geometry

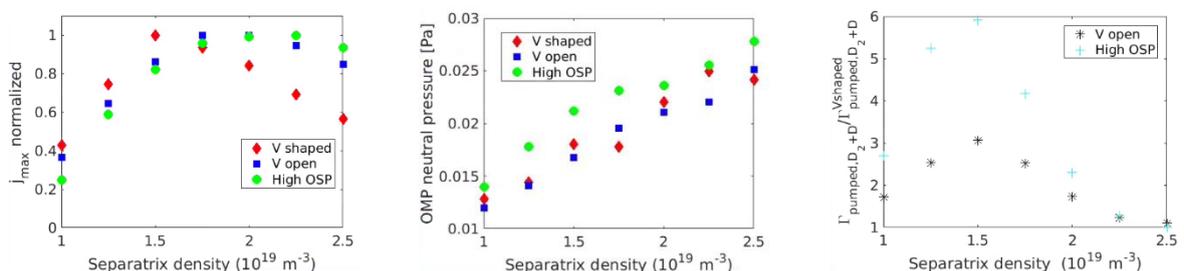


Figure 4: On the left, the normalized peak current density as a function of $n_{sep,OMP}$ for the three cases: V-shaped, V-Open and High SP. In the center, the neutral pressure at OMP in the density scan. On the right, the ratio of the Γ_{pumped,D_2+D} of the proposed solution over that of the reference V-shaped.

To increase the pump capability of the system, we propose two different solutions: an opening of the V-shaped corner (V-open) and an upward shift of the outer strike point by 8 cm to locate it above the corner (HighSP). A $n_{\text{sep,OMP}}$ scan in pure D with $P_{\text{in},\rho=0.9} = 5\text{MW}$ is performed to characterize the divertor plasma behaviour.

Figure 4 shows the results in terms of detachment achievement. In the V-shaped geometry, the roll-over of the peak particle flux is obtained at low separatrix density. This is related to the trapping of the neutral particle in the corner, which helps the detachment in the strike point region by enhancing the momentum loss by plasma-molecule charge exchange collisions. The worst performance in terms of detachment achievement is the High SP case. Indeed, in the High SP the neutral density at OMP is higher than in the other two configurations. By considering the plasma at the roll-over point in the three cases, we have an improvement of the neutral leakage in V-shaped by $(p_{\text{neut,OMP}})^{\text{Vshaped}} / (p_{\text{neut,OMP}})^{\text{V-Open}} = 0.85$ and $(p_{\text{neut,OMP}})^{\text{Vshaped}} / (p_{\text{neut,OMP}})^{\text{HighSP}} = 0.7$. In terms of pumping rate, a strong increase is observed by changing the divertor geometry at low midplane density by a factor of up to 3 for the V-open and up to 6 for the HighSP. This is related to the possibility for the neutral molecules to escape and penetrate the sub-divertor, while in the case of V-shaped they are well trapped in the corner. This effect tends to disappear at higher densities since the ionization front in the V-shaped case locates above the corner, allowing the neutral molecules to fill the sub-divertor region.

Conclusions

The SOLPS-ITER modeling of JT-60SA Scenario 2 with Ne seeding has shown low D pumping rates, close to the particles injected by the NBI. The V-shaped outer divertor corner, designed to favor the detachment at low midplane plasma density, is particularly effective in trapping neutral particles in the corner, thus enhancing the momentum loss in the strike point region. However, the particle cannot escape as long as the ionization front is in the corner. A change in the divertor geometry, either obtained by opening the corner or by moving the strike point, can lead to an increase in the pumping rate at the price of higher neutral leakage and higher roll-over midplane density, as shown in the pure D plasma upstream density scan. The analysis of impurity seeding in the two proposed solutions is currently ongoing to assess how the change in the divertor geometry can affect more realistic divertor plasma scenarios in terms of detachment achievement, neutral and impurity compression, and pumping capabilities of the system.

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