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Helium exhaust studies at JET in reversed B

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Introduction - The removal of helium in future fusion devices with significant alpha particle production is essential. The removal of the "ash" has to be efficient enough to provide a "clean" core plasma and to avoid a high throughput of the fuelling gas in the pumping system. We concentrate in this paper on the transport in the plasma edge, i.e. scrape-off layer and divertor. For an overview of the work done so far on this topic, the reader is referred to [1] and references therein. The exhaust studies in reversed B are aimed at understanding the helium and deuterium edge transport towards the divertor by comparing the reversed and the forward B configurations.

The strike point position with respect to the pumping slot has a strong impact on the pumping efficiency (c.f. [1, 2]). This is mainly due to geometric effects. This fact can be exploited for the analysis of particle transport in the scrape-off layer. We consider four different strike point positions as shown in figure 1. If for example a directed flow in the SOL exists, we would expect to see this in a change of the particle compression into the divertor when switching between the two asymmetric strike point configurations.

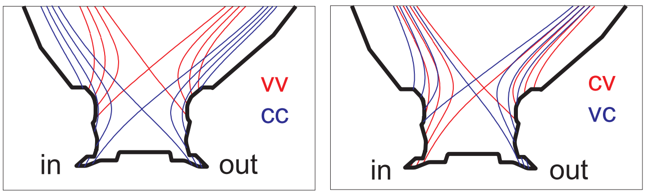

Figure 1: *The four configurations of the strike point positions (e.g.* **vc** *means inner strike point at the vertical target and outer strike point at the corner position).*

Quantitative description of the particle exhaust - In order to achieve adequate helium pumping, it is necessary to maximise the helium pressure in the pumping chamber of the divertor. Additionally it is desirable to have a high helium concentration in the pumping chamber in order to keep the amount of fuel cycling in the pumping system as low as possible. To quantify these requirements the particle compression into the divertor and the helium enrichment have been used as figures of merit. The first quantity is defined as (e.g. [1]) the ratio between the neutral density in the subdivertor n^0_{subdiv} and the ion density in the plasma n^+_{plasma}:

$$C_p = n^0_{subdiv}/n^+_{plasma}\ . \tag{1}$$

The second quantity is the ratio of the helium to deuterium compression, which is to good approximation the ratio between the helium concentration in the divertor and the plasma core:

$$\eta = C_p^{He}/C_p^D\ . \tag{2}$$

Figure 2 shows the time traces of these parameters for the four strike point configurations. The discharges were heated with 5 MW NBI power, the line averaged density is about $2.5\times10^{19}\mathrm{m}^{-3}$, plasma current is 2.4 MA and the toroidal field is 2.5 T. A flat-top phase (indicated by the green regions) establishes after each injection of helium gas. The core helium concentration ranges from 10% to 40%. It is usually measured by CXRS, however, for the forward field reference pulses this diagnostic was not available. We therefore estimated the core concentration for these cases from the injected amount of helium assuming a fuelling efficiency of 100%. This value was approximately found in the cases with CXRS. The neutral pressure of deuterium and helium in the pumping chamber of the divertor was measured by Penning gauge spectroscopy [3]. Unfortunately, the discharges compared here differ in confinement: the discharges in forward B switch to H-mode with small dithering ELMs if at least one strike point is placed in the divertor corner, whereas the discharges in reversed B stay in L-mode for all configurations. However, since the ELM's are small, this difference should not affect the analysis performed here. From the lefthand figure we see that the compression for both species drops significantly, in forward and reversed B configuration when the two strike points are shifted upwards onto the vertical target plates away from the pumping slot. The righthand figure shows the cases with the asymmetric strike point positions. We find for the forward B case that the compression for deuterium is higher if the outer strike point is placed in the corner. For the reversed B case it is higher if the inner strike point is placed in the corner. The same is true for helium, although the difference is not that pronounced for forward B. This suggests that for forward B the inner divertor leg has a higher pumping ability compared to the outer divertor leg and vice versa for reversed B.

For a more detailed analysis, we will now take a closer look at the definition of particle compression. We take for the ion density the volume averaged value and obtain for the particle compression $C_p = V_{plasma}N_{subdiv}/V_{subdiv}N_{plasma}$. The compression can be written in terms of the particle confinement time τ_p, the efficiency for the divertor pumping ϵ_{pump}, the wall pumping ϵ_{wall} and the divertor screening ϵ_{screen} as

$$C_p = \frac{V_{plasma}}{V_{subdiv}}\frac{\tau_{pump}}{\tau_p}\frac{(1-\epsilon_{wall})\epsilon_{pump}}{1-(1-\epsilon_{pump})\epsilon_{screen}}\ . \tag{3}$$

This representation allows one to separate the core transport from the edge and divertor effects. The compression is a function of the particle confinement time τ_p, but it depends also on the divertor properties: good screening abilities and a maximised pumping efficiency result in a high C_p. The divertor pumping efficiency is defined as the ratio of the ion flux arriving at the target plates $\Gamma_\parallel$ and the neutral flux being pumped by the divertor pump

$$\epsilon_{pump} = \frac{N_{subdiv}/\tau_{pump}}{\Gamma_\parallel}\ . \tag{4}$$

The divertor cryogenic pump - if no argon frost is applied - is capable of pumping the deuterium but not the helium. A characteristic pumping time τ^D_{pump} of 22 ms can be derived from the

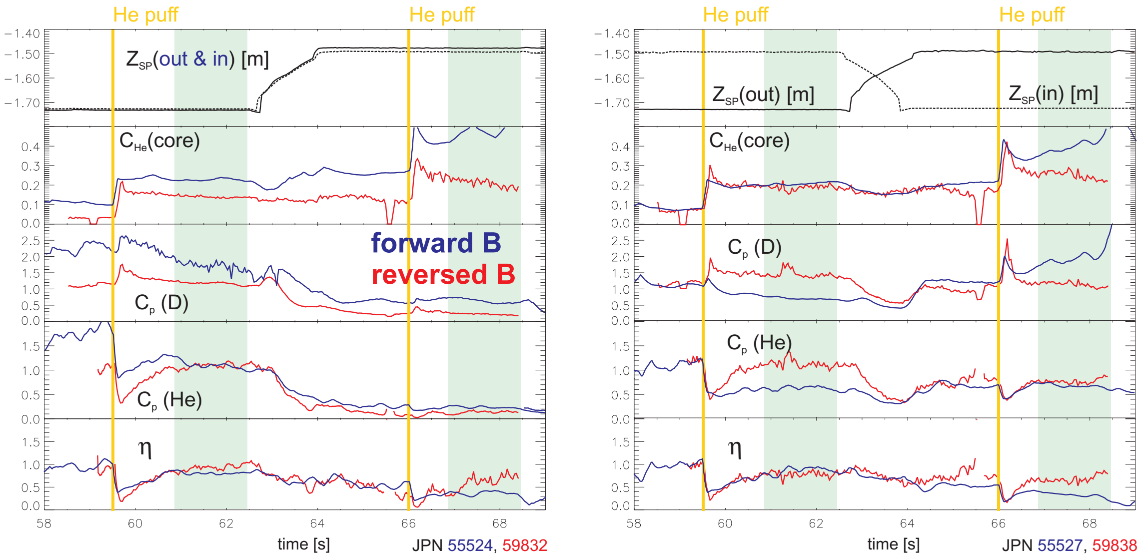

Figure 2: *Typical time traces of the strike point position, the helium concentration, the pumping efficiency, the compression and the helium enrichment. The lefthand figure shows the symmetric strike point configurations (cc and vv), the righthand figure shows the asymmetric configurations (vc and cv). The relevant flat-top regions are marked with the green boxes.*

measured pumping speed of about $110\mathrm{m}^3\mathrm{s}^{-1}$ and the volume of the subdivertor of about $2.5\mathrm{m}^3$. The ion flux to the divertor is measured by spectroscopic means, observing the D_α light and a HeI line at 668 nm. The particle fluxes are deduced using conversion factors of 20 ionisations per photon for deuterium and 110 for helium. The measured pumping efficiencies are in the range of a few percent and we write C_p in the limit $\epsilon_{pump} \rightarrow 0$:

$$C_p = \frac{V_{plasma}}{V_{subdiv}} \frac{(1-\epsilon_{wall})}{\tau_p(1-\epsilon_{screen})} \tau_{pump}\epsilon_{pump} + O(\epsilon^2_{pump}) \;, \tag{5}$$

Figure 3 shows the helium and deuterium compressions as a function of the pumping efficiency multiplied by the pumping time, in order to give values independent of the pumping speed. The particle compression is, within the error bounds linear with the pumping efficiency. The effective confinement time $\tau_p^{eff} = \tau_p(1-\epsilon_{screen})/(1-\epsilon_{wall})$ (c.f. equation 5) is 17 ms (forward B) to 18 ms (reversed B) for deuterium and 39 ms (forward B) to 58 ms (reversed B) for helium. The shaded area indicates the deviation from these values by 25%. The C_p values for the *vv* configuration in forward field are higher because of the confinement degradation when switching to L-mode. The wall pumping can be assumed to be zero for helium. Thus, it follows that either the core transport is faster for deuterium than for helium and/or the screening efficiency is higher for deuterium. The latter is plausible since the ionisation energy is higher for helium.

Since the particle compression is linear with pumping efficiency, changes in the overall divertor screening or the core confinement can be excluded when switching between the different strike point positions. The pumping efficiency itself depends mainly on the geometry. Thus if the particles preferentially flow to the inner divertor leg (forward B) or the outer divertor leg (reversed B) the pumping efficiency will be highest in the case of asymmetric strike point positions, if the inner or, respectively, the outer strike point is placed into the corner. Such flows are indicated by Mach probe measurements [4]. However, the same is true if the screening efficiency is different in the inner and the outer divertor legs, which would also result in asymmetric particle fluxes to

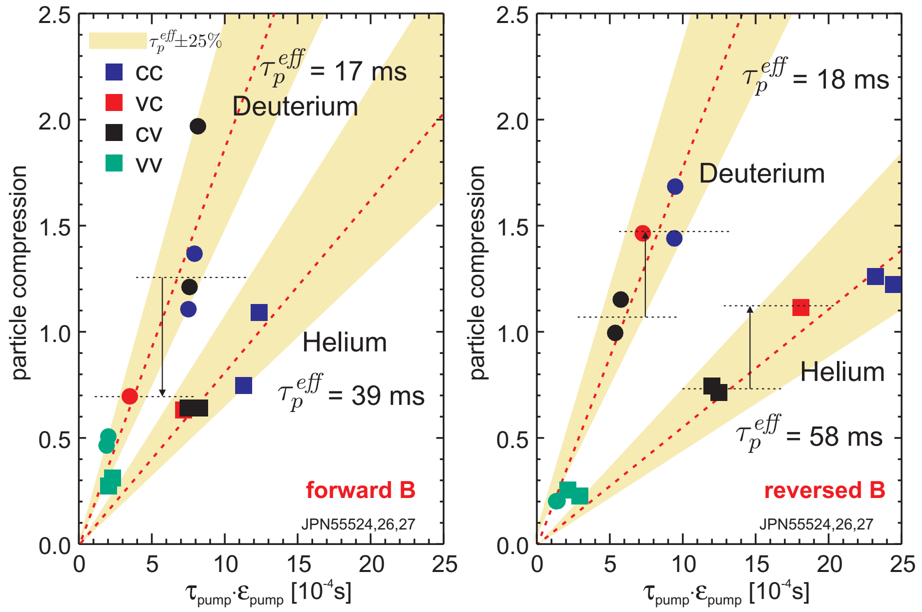

Figure 3: *Particle compression for helium and deuterium as a function of the pumping efficiency multiplied by the characteristic pumping time.*

the divertor target. Nevertheless, to obtain asymmetric screening efficiencies a driving force is required to produce asymmetric plasma parameters in the divertor. Both mechanisms - particle flow in the SOL and/or asymmetries in the divertor plasma - result in a higher particle flux in the inner divertor leg for forward B and in the outer leg for reversed B, which is confirmed by the ion saturation current measured by the target probes. The existence of such asymmetries has been reported, for example, in [5].

The maximum pumping efficiency achieved for deuterium with the *cc* configuration is about 4%. The *vv* configuration results in less than 1% pumping efficiency. The helium enrichment is around $0.3 - 1.1$ and shows no clear dependence on the direction of B. In the forward B case it tends to drop with time, which might be related to an overestimation of the helium core concentration. However, the enrichment factor cannot be taken as truly representative without the application of helium pumping, which would significantly reduce the enrichment .

Conclusions - It is the inner divertor leg which makes a larger contribution to particle pumping for forward B and it is the outer divertor leg in the case of reversed B. This results in a higher pumping efficiency and a higher particle compression for deuterium and helium if the inner (forward B) or outer (reversed B) strike point is positioned close to the pumping slot. A particle flow in the scrape off layer is a good candidate to explain the different pumping abilities of the inner and outer divertor. These results might also be explained by different screening efficiencies in the two divertor legs, caused by other mechanism leading to or enhancing the divertor asymmetries.

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