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** See annex of J. Pamela et al, "Overview of JET Results ",*
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1. INTRODUCTION

As shown in [1, 2], impurities can be prevented from penetrating into the plasma core in JET ELMy H-mode discharges if the deuterium gas puff exceeds a certain level. In [2] this was explained by noting that the neo-classical convective velocity within the edge transport barrier changes from inward- to outward-directed when the deuterium density at the last closed flux surface exceeds a critical level, which is reached by increasing the deuterium gas puffing. However, it is also true that for the impurities to reach the last closed flux surface they first have to penetrate the Scrape-Off Layer (SOL). The goal of this paper is to evaluate other processes, within the SOL, which can also contribute to impurity screening along with the neo-classical convective velocity within the Edge Transport Barrier (ETB).

There are several mechanisms in play which can influence the impurity behaviour in the SOL. Impurities can be prevented from penetrating into the core by the existence of collisional classical friction between impurities and the flow of main ions towards the target plates. In the SOL the impurities can be compressed by the deuterium flow at the target plates where they can be pumped away more efficiently, or at least pushed away from the separatrix. In contrast, the parallel component of the thermal force usually drives the impurities in the opposite direction. The impurity compression was observed in DIII-D [3] and was dependent not only on the main gas puffing level but also on the position of the gas inlet (with puffing from the outboard mid-plane being the most effective). This result was not found in ASDEX Upgrade [4]; there it was observed, though, that the level of impurity compression near the targets increases with the divertor neutral gas density. Previous analysis of JET discharges drew a similar conclusion as for DIII-D, but only for L mode plasmas. For medium density H mode the difference in the main gas puff did not result in significant variation in impurity compression [5]. This was explained by the strong intrinsic convective SOL due to particle drift flow as measured at JET [6].

In this paper we study numerically using a 2D transport code EDGE2D/NIMBUS [7] the impurity transport in the SOL and the mechanisms that can prevent them from reaching the plasma core: the compression of impurities into the target plates, the impurity neutral leakage for JET MarkII divertor H modes plasmas. This study includes plasmas with different deuterium densities, input powers and the influence of the deuterium puff positions: at the top of the vessel, at the divertor, at the high field side and low field side. These analyses use a 2D code EDGE2D [7] based on the Braginskii ionised fluid approximation for the Boltzmann system of kinetic equations [8]. This code is coupled with a Monte-Carlo code, NIMBUS, which calculates the particle and energy sources due to neutrals recycled at the targets and chamber walls. The EDGE2D/NIMBUS code has been successfully used to model the SOL [6, 9].

II. TRANSPORT EQUATIONS AND PREDICTIVE MODELLING

The computational domain of EDGE2D comprises the entire SOL with the private region below the X-point and a small region inside the last closed flux surface that includes the ETB and a small region of plasma core.

Braginskii's equations used in EDGE2D do not describe well the perpendicular transport as this is mainly anomalous. The prescribed ad hoc perpendicular transport is typical for H mode plasma and the same for all species (main ions and impurities). The heat fluxes are the same for the ions and electrons. The particle diffusion and the thermal diffusivity have different values for each plasma region: plasma core, ETB and SOL. In the plasma core up to the top of the barrier, particle diffusion is D = 0.5 m^2/s and χ = 1.5 m^2/s; within the ETB D = 0.05 m^2/s and χ = 0.05 m^2/s, (values close to neo-classical) and in the SOL D = 0.25 m^2/s and χ = 0.35 m^2/s.

The main objective of this study is to verify the conditions which might prevent impurity penetration to the core; one of them is that the friction that is downward directed and parallel to the magnetic field be greater than the thermal force that is upward directed. The greater the main density is at the last closed flux surface the greater is the fiction force. The other mechanism might be the position of the main gas puffing. To study this effect we used the last closed flux surface as a control variable in the EDGE2D code. The simulations started with the density of $n_i(a) = 1.0\times10^{19}$ m^{-3}, and it was increased in each simulation until the plasma was fully detached. It is possible to simulate different main ion puffing positions in EDGE2D. In this study we used four positions: at the top of the vessel, in the private region, at the high field side (inner mid-plane puff) and at the low field side (outer-mid plane puff). For the impurities we use the total ion particle content of 6.0×10^{18} particles for Neon and 1.6×10^{19} particles for Carbon in the whole EDGE2D computational domain of a volume of 25 m^{-3}. Neon was puffed locally at the low field side. The impurity density at the innermost flux surface was considered to be zero or $\nabla n_z = 0$ for all ionisation states. In these simulations we did not include the chemical sputtering; for simplicity only the yield from the wall and divertor targets was considered.

To evaluate the retention efficiency of the impurities in the divertor region for the different simulations we introduce compression and enrichment factors, defined as [10]:
$C_p = n^0 \text{(divertor)} / \Sigma n^{i+} \text{(a)}$ and $\eta_{imp} = C_{imp}/C_D$ respectively. $n^0(divertor)$ is the neutral particle density in the divertor region and n^{i+} is the ion particle density of the i^{th} ionised state at the last closed flux surface at the outer mid-plane.

3. RESULTS FROM THE SIMULATIONS

We first discuss the results for the simulations with $n_z = 0$ and 8.64 MW NBI power. The perpendicular ion impurity fluxes to the plasma core (averaged over a magnetic surface) are reduced as the density increases and even change direction from inward to outward when the top puff is used (Figure 1(a)). This reduction is negligible when the divertor main ion puffing position is used. Although the ion impurity flux is reduced with increasing main ion density, the neutral influx of impurities to the core increases significantly for densities higher than $n_i(a) = 3.0\times10^{19}$ m^{-3} at the separatrix. This is because the T_e decreases with the density at the targets and the ionisation rate decreases. This neutral leakage leads to an impurity penetration into the plasma core but there is a 20% reduction in the impurity influx at a density $n_i(a) = 3.0\times10^{19}$ m^{-3} compared to a flux of $\Gamma_{max} = 6.26\times10^{19}$ p/s at the low density of $n_i(a) = 1.0\times10^{19}$ m^{-3} when outer mid-plane puffing is used. This can be interpreted as that the compression and enrichment at the outer divertor target are higher for the optimum main ion density than for the other simulation cases (Figures 2(a-d)). Figures 2(a) and 2(b) show the compression at the inner and outer divertor; Figures 2(d) and 2(d) show the enrichment at the inner and outer divertor. The compression at the inner target is higher when the inner main ion puff was used but the enrichment is higher for the outer puff at plasma densities closer to the detachment level.

The neutral density leakage was reduced and even removed completely when we performed simulations with higher input powers of 12.96MW and 17.28MW and zero impurity density at the innermost flux surface. Figure 3 shows that the total ion density is concentrated in the divertor region when the plasma reaches detachment and the highest power is used. This is because the T_e is high enough at the SOL for the impurity neutrals to be ionized. The ions are concentrated in this region because the thermal force is fully compensated by the friction force. This leads to a significant (around 50 %) reduction of the impurity flux to the plasma core: much higher than for the simulations with lower input power (Figure 4(a)). The main ion density with the highest enrichment at the outer divertor target factor increases with the input power and its maximum value decreases.

Figure 5 shows the compression (a) and enrichment (b) for the outer divertor target of Neon (recycled impurity) and Carbon (non recycled impurity). One can conclude that both parameters are higher for C and that the maximum is reached at a lower main ion density for the C case. This is probably because we used more C particles than Ne particles in the simulation due to charge exchange.

CONCLUSIONS

The impurity compression increases with density before the beginning of detachment of the plasma, and for all the different input powers used in the simulations. The outer deuterium puffing position is more efficient in removing impurities. The reduction of impurity flux to the plasma core reaches 50% within the density scan when the highest power is used. The radiation in the plasma core reduces when the input power increases; this is due to the fact that the Neon neutrals are completely ionized within the SOL. For lower input powers, although there is a change from an influx to an outflux from the core of impurity ions there is a significant leakage of neutrals that penetrates into the plasma core, leading to possible radiation collapse of the plasma. The conclusions are similar when we use $\nabla n_z = 0$ as boundary condition in the simulations to the ones when we use $n_z = 0$; the difference is that the density limit is higher for the $\nabla n_z = 0$ case. This is because there are more impurity particles in the plasma core in the case of $\nabla n_z = 0$ and the T_e in the SOL does not decay so rapidly with the density. Better boundary conditions could be obtained from a combination of EDGE2D and JETTO, a task that is anticipated for the future.

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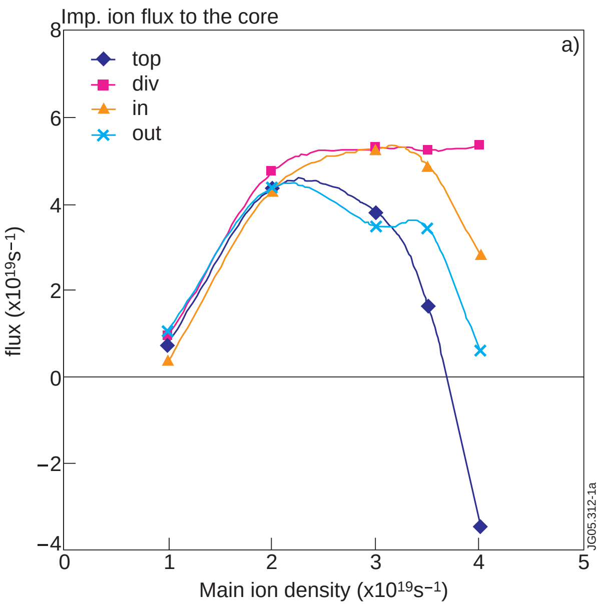

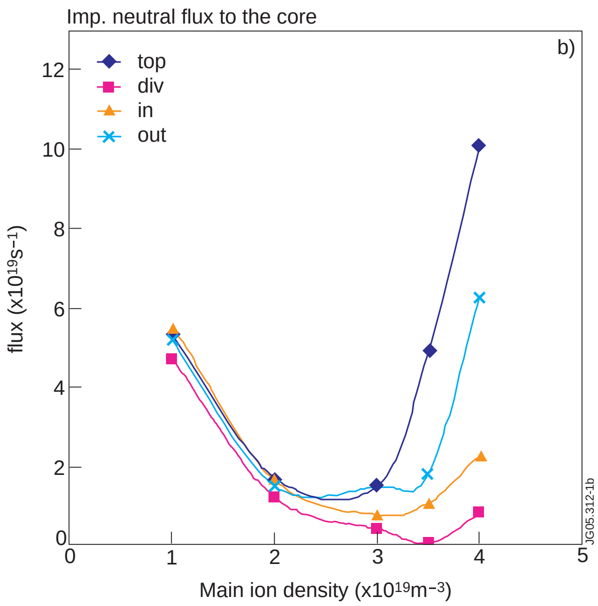

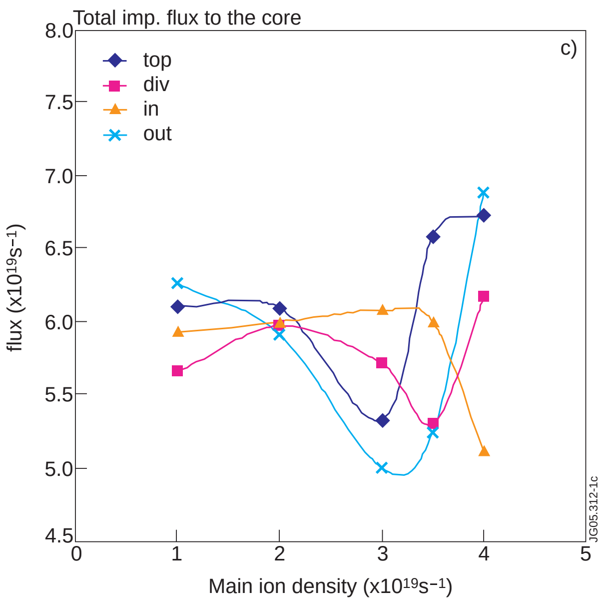

Figure 1: Perpendicular particle flux to the core for: a) impurity ions; b) neutral impurity, and c) the sum of the neutral and the ion fluxes.

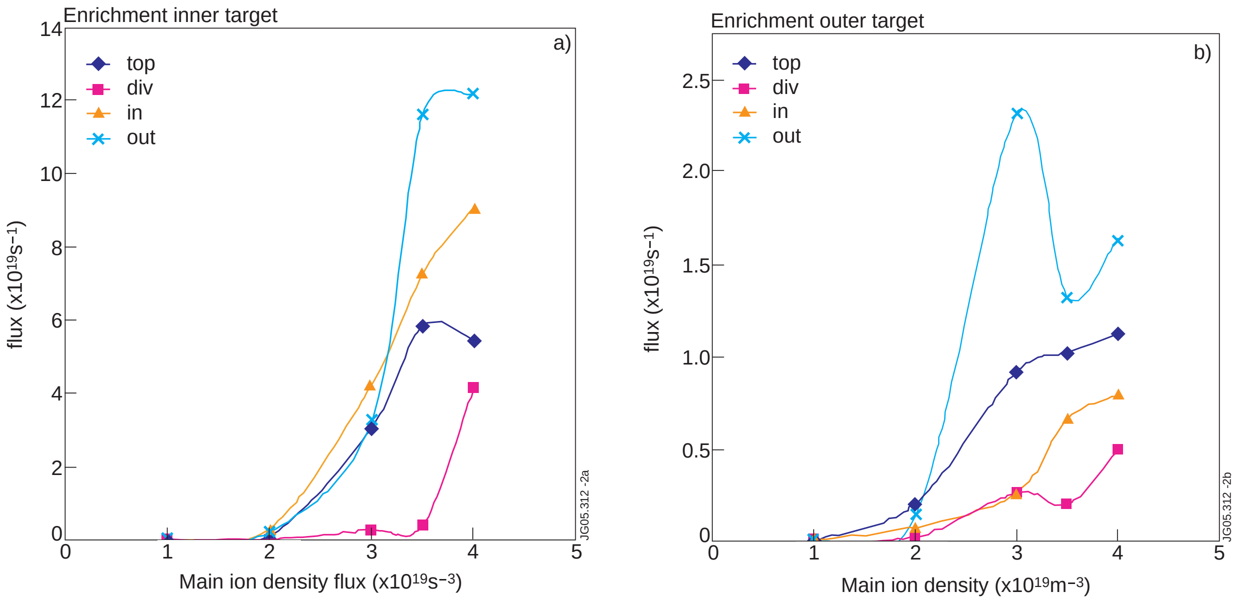

Figure 2: Enrichment as function of density for the four main ion puffing positions, divertor, top, inner mid- plane and outer mid-plane: a) inner target; b) outer target.

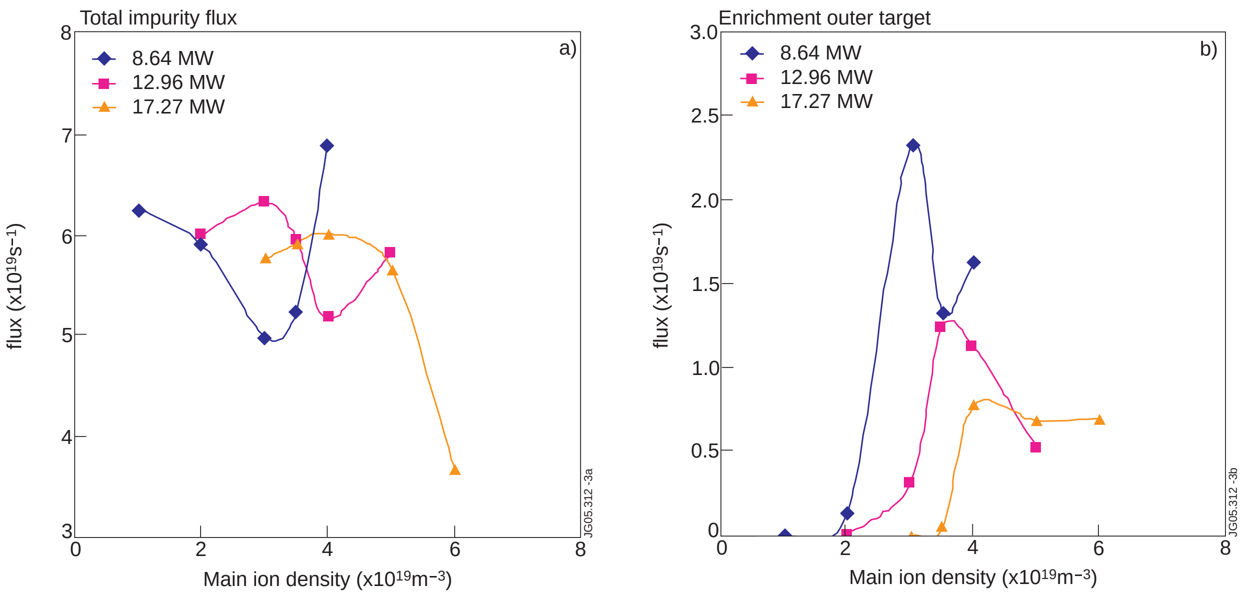

Figure 3: Total perpendicular impurity flux to the plasma core averaged along the seperatrix as a function of density for the different input powers, 8.64MW, 12.96MW and 17.28MW when the top puffing was used. b) Enrichment.

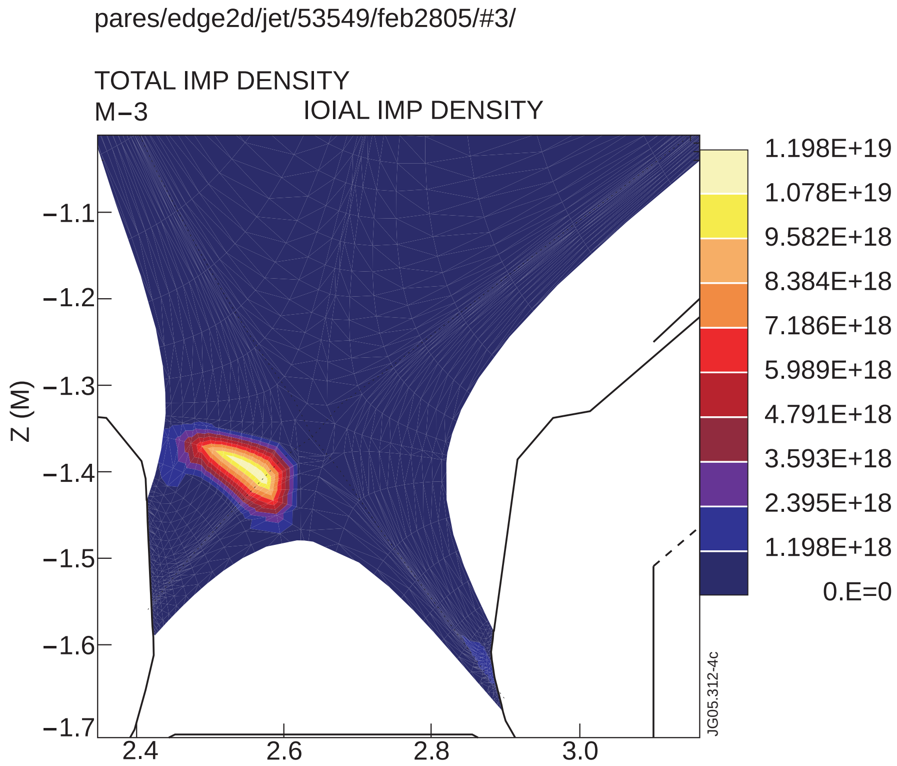

Figure 4: Total impurity density for the contour plot for the simulation with the highest power and main ion density.

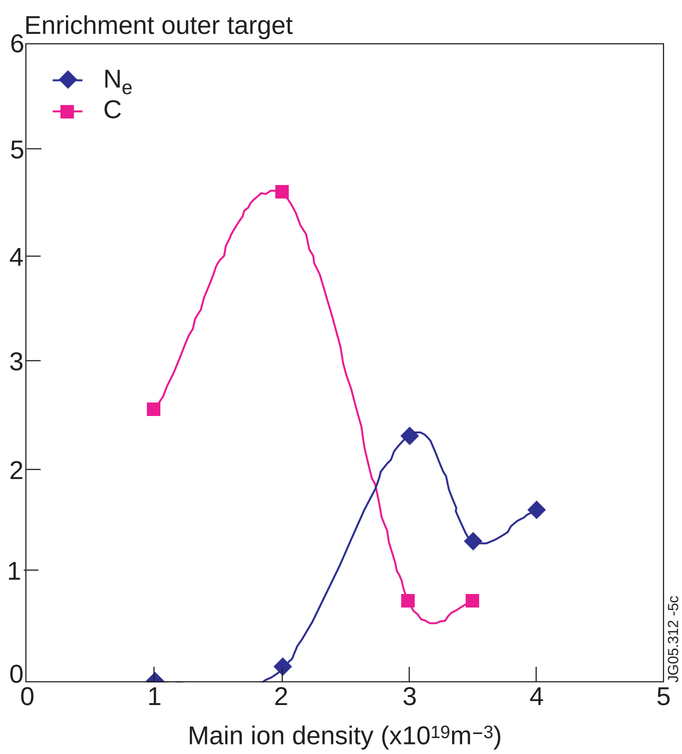

Figure 5: Enrichment for the outer target for the cases with a recycled impurity (Ne) and non recycled impurity (C).