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Impurity retention under enhanced recycling conditions in W7-AS

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Introduction

In contrast to pre-divertor limiter operation, the island divertor in W7-AS enabled plasma density control even in the presence of a strong NBI-source, showing a significant improvement of the recycling conditions. Impurity radiation could be kept within the island SOL to enable a stable partial detachment without remarkable loss of the global energy content [1]. The divertor operation led to the discovery of the HDH-regime [2] characterized by high density and good energy and low impurity confinement [3]. Based on EMC3/EIRENE simulations and simple models, the paper presents a detailed analysis of the neutral and impurity transport behavior in the island divertor under different recycling conditions, aimed at identifying the role of the recycling neutrals and the intrinsically released impurities in improving the global plasma performance. Special attention is paid to the impurity screening effect of edge islands. It is found that the ratio of friction to thermal forces depends strongly on the recycling conditions. For low recycling, low density plasmas, thermal forces usually dominate which draw the impurities towards the separatrix. In the high-density case, friction prevails against the thermal forces and the strengthened plasma flow resulting from the enhanced recycling flux drives impurities back to the targets. The carbon concentration around the separatrix is reduced by more than one order of magnitude with respect to the low density case, showing a strong screening effect of the magnetic islands on impurities under high-density conditions. Although it is not clear how the impurity concentration in the core correlates with the impurity density at the separatrix, the impurity flushing in the islands is certainly favorable for reducing the impurity density in the core, thereby helping to prevent a high-density plasma from falling into radiation collapse.

Recycling conditions

Gas-puffing needed to increase the plasma density initially provides a primary particle source for the SOL and leads to an enhancement of the recycling process. The core plasma is fuelled indirectly by the recycling neutrals, which depends strongly on SOL transport. Fig.1 shows the dependences of the total recycling flux Γ_{recy} and core-fueling rate Γ_{core} from the recycling neutrals on the separatrix density n_{es}. The results are obtained by EMC3/EIRENE simulations for hydrogen plasmas with the standard divertor configuration based on the vacuum field. A SOL power of 1.2 MW is used, which is split equally between ions and electrons. A sputtering coefficient of 2% for carbon is assumed.

Further conditions are D=0.5 m^2/s for both carbon and hydrogen and $\chi_i = \chi_e = 3D$. In the calculations, n_{es} is increased until the plasma approaches detachment. The explanation of the linear dependence of Γ_{recy} on n_{es}, the Γ_{recy}-roll-over effect and detailed studies on the neutral and impurity transport behavior in detached plasmas can be found in previous papers [4, 5]. We restrict our attention to the attached case. Γ_{core} is normalized to the NBI-source in order to show the relative importance of the core fueling by the recycling neutrals. In low n_{es}-range ($n_{es}<2\times10^{13}$ cm^{-3}), the SOL plasma is transparent for the recycling neutrals so that the almost linear dependence of Γ_{core} on n_{es} reflects actually the linear increase of the recycling flux. Increasing n_{es} increases the CX and ionization activities inside the islands and leads to a movement of the ionization front towards the targets. If this happens, although Γ_{recy} still increases, Γ_{core} drops until the ionization front detaches from targets due to the temperature effect. If one believes that the rollover of the core fueling rate Γ_{core} with n_{es} is responsible for the n_{es}-jump observed in hydrogen plasmas [2], one would face the difficulty to explain the smooth path in deuterium plasmas [6]. The drop of Γ_{core} is a result of the island neutral screening effect, which would become moderate and eventually disappear with decreasing the island size.

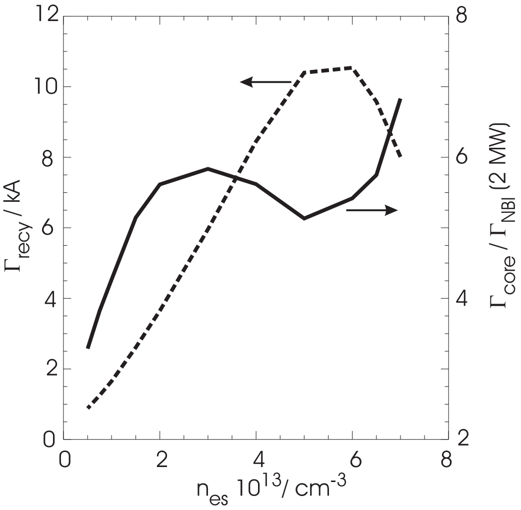

Fig.1: n_{es}-dependences of the total recycling flux and the recycling flux penetrating into the core.

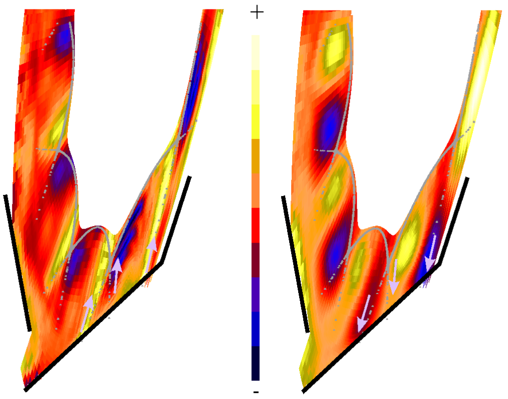

Fig.2: Distributions of impurity parallel velocities resulting from thermal forces and friction for n_{es}=1.5 (left) and 5×10^{13} cm^{-3} (right). The phase distribution of the dominating thermal force (left) results in an inwards-directed convection for impurities, as indicated by the arrows. The flow is completely reversed for the friction-dominated case (right).

Impurity retention in the island SOL

The balance between thermal force and friction determines the parallel flow direction of impurities and thereby influences the impurity distribution in the SOL:

$$V_{Z\parallel} = V_{i\parallel} + \frac{\tau_{Zi} Z^2}{m_Z}\left(0.71\nabla_\parallel T_e + 2.2\nabla_\parallel T_i\right) + \frac{\tau_{Zi} Ze}{m_Z} E_\parallel - \frac{\tau_{Zi}}{n_Z m_Z}\nabla_\parallel T_i n_Z . \qquad (1)$$

The first term on the right side of eq. (1) is the parallel flow velocity of the background ions, the second one thermal forces from electrons and ions, the third one the parallel E-field determined by electron momentum balance and the last term the pressure gradient of the impurities (T_Z=T_i). While a thermal force resulting from a parallel temperature gradient tends to draw impurities upwards towards the high temperature region (upstream), a frictional plasma flow drives the impurities back to the target (downstream). Here, we ignore the flow reversal effect discussed in tokamaks. The dominating thermal force comes from ions due to the poor classical conductivity with respect to electrons. As the ratio of friction to thermal force is determined by the ratio of the ion classical convective to conductive heat flux, both increasing the plasma flow and reducing the conductive heat flux favor the impurity screening effect of a SOL. Fig. 2 compares the parallel velocities of carbon resulting from thermal forces and friction between a low and an enhanced recycling case with n_{es}=1.5 and 5×10^{13} cm^{-3}, respectively. At lower n_{es}, the thermal force dominates over the friction and exhibits a phase distribution among the island fans which results in an inwards flow of impurities, as indicated by the arrows. At higher n_{es}, the friction prevails against the thermal forces and the phase distribution of the net-force is completely reversed. The impurity flow is changed from inwards- to outwards-directed in almost the whole island SOL. The 'flow reversal' makes a strong impact on the impurity distributions. Fig. 3 shows the corresponding carbon density (sum of all ionization stages) distributions which are normalized to the total carbon production rate in order to isolate the transport effects from production processes. The dominating thermal force in the lower recycling case draws the carbon towards the separatrix, leading to an impurity accumulation there, whereas the plasma flow, once exceeding the thermal force, drives the impurities outwards and keeps them around the targets. This 'flow reversal' of impurity reduces the carbon density at separatrix by more than one order of magnitude.

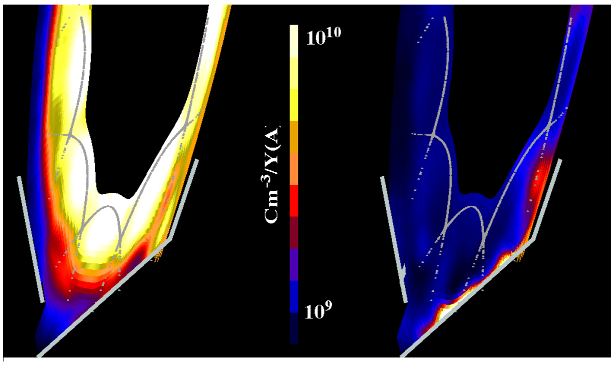

Fig.3: Distributions of carbon density normalized to carbon production rate for thermal-force dominated (left) and friction dominated case (right). The thermal force draws carbon inwards, leading a density accumulation at the separatrix, while the friction forces carbon back to the target.

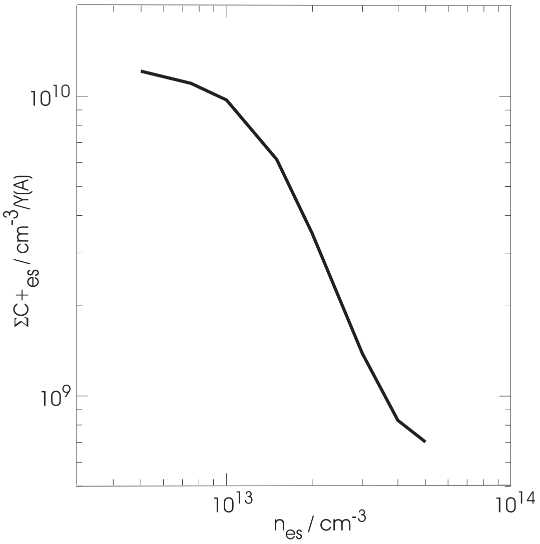

Fig. 4: Carbon separatrix density as a function of n_{es}. The carbon density at separatrix drops quickly once the friction becomes dominating.

Unlike in a tokamak divertor, the cross-field transport associated with the small internal field-line pitch in W7-AS can, under certain conditions, significantly reduce the ion classical heat conductive flux. The cross-field heat conduction becomes even dominant under high density conditions (or equivalently low-T_i conditions): $n_e > k_i T_i^{5/2} \Theta^2 / \chi_i$

where Θ is the internal field-line pitch. Because of the rather small Θ ($\sim 10^{-3}$) in W7-AS, it is possible to reach the above condition in the whole islands. Once this condition is established, the classical heat flux is strongly reduced because of the high sensitivity of the conductivity to the temperature and the related thermal force disappears. Fig. 4 shows this transition process. One sees a sharp decrease of the carbon density at the separatrix when the friction becomes dominating over the thermal force in the n_{es}-range of $2\text{-}3\times10^{13}$ cm^{-3}.

Discussion

The force balance analysis made in this paper is based on classical theory, while the cross-field heat conduction, which plays a key role in reducing the thermal force, has to be considered to be turbulence-induced. Until now, there is no experimental evidence showing that the ion cross-field heat conduction really exceeds the parallel classical one. However, the strong drop of the electron temperature at the separatrix observed at even higher n_{es} [7] would support this theory. The effective reduction of the parallel conductive heat flux is associated with the small internal field-line pitch of the islands, which is obviously a stellarator-specific issue. Besides the transport effects, impurity production, which is associated with rather complex processes and not addressed in this paper, is essential to finally determine the absolute impurity density. If one assumes that the total carbon production rate increases linearly with Γ_{recy}, the impurity screening effect resulting from transport, i.e. the reduction of carbon density at the separatrix, would be, to a large extent, compensated by the increased carbon production rate. This assumption for carbon is reasonable because of chemical effects. In addition, EMC3 detachment-related simulations [5] based on a linear ansatz for carbon release agree well with experiments. Nevertheless, light impurities like carbon do not account for core radiation. A core-peaked radiation profile should be associated with heavier impurity species. For heavy impurities like iron, a cold island plasma is essential for reducing the sputtering yield, which can be realized under enhanced recycling conditions.

The impurity transport in the SOL provides the necessary boundary conditions for the core through which it enters the impurity global confinement process. For example, for a test, source-free impurity, if governed by convective/diffusive processes determined by a given background plasma, the impurity density at the separatrix will determine the level of the impurity density in the core (linear coupling), while the transport determines the shape of the density profile.

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