Effect of field reversal on carbon migration in the outer divertor of ASDEX Upgrade

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Introduction

Migration of impurities determines several critical boundary plasma issues such as net erosion of plasma-facing components, fuel retention and impurity screening. A series of $^{13}CH_4$ injection experiments has been performed in ASDEX Upgrade to investigate carbon migration in an ITER-relevant, vertical target geometry. The experiments have been modelled using the SOLPS5.0 [1] and ERO [2] code packages. Previous work has identified the importance of cross-field drifts on the local re-deposition patterns [3, 4]. In this paper, we illustrate how the divertor electric field influences the transport pathways in the divertor plasma and discuss the effect of magnetic presheath on local re-deposition.

Experiments and Modelling

Four $^{13}CH_4$ injection experiments were performed during the 2007-2009 ASDEX Upgrade campaigns to investigate impurity migration mechanisms in low-density L-mode conditions [4–7]. The tracer was injected into 1 or 2 poloidally separated locations in the outer divertor plasma, and well-resolved 2D patterns of local ^{13}C deposition were obtained using post-mortem ion-beam measurements. The effects of plasma conditions and cross-field drifts on ^{13}C migration were investigated using both forward (ion $\nabla\mathbf{B}$ drift towards the lower divertor) [6, 7] and reversed B_t and I_p [4, 5].

The edge plasmas were modelled with the 2D plasma fluid – Monte Carlo neutrals code package SOLPS5.0, with impurities and cross-field drifts included in the solutions. After careful comparison against all relevant edge plasma measurements, the steady-state plasma solutions were integrated into kinetic 3D ERO simulations of the tracer trajectories. ERO is a Monte Carlo impurity tracing code that takes into account material-dependent reflection and re-erosion of impurities in a limited simulation volume [2]. It, therefore, evaluates the local re-deposition patterns, which have been previously benchmarked against surface analyses.

The divertor electric field is calculated from the plasma potential obtained from SOLPS5.0

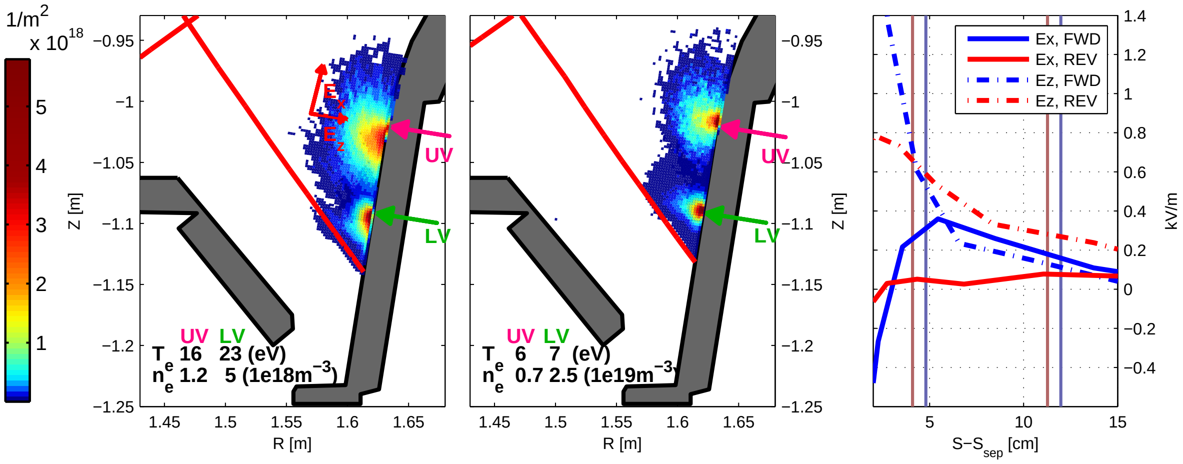

Figure 1: Modelled density of ionized ^{13}C in the 2007 forward field (left) and the 2009 reversed field (middle) experiments (see experimental and modelling details in [4, 6]). The large arrows denote the injection locations; the local plasma parameters are given in the lower left corners of the figures. The figure on the right shows the electric field components along and towards the surface (see also left figure), with the valve positions indicated by the blue and red vertical lines in forward and reversed field, respectively.

simulations. The plasma potential varies in 2D, giving rise to electric field components along and towards the surface, $\mathbf{E}_x$ and $\mathbf{E}_z$, respectively, see figure 1. The potential solution from SOLPS5.0 does not include the regions of Debye sheath (∼0.01 mm thickness) and magnetic presheath (∼1 mm thickness) next to the target, where a strong electric field exists towards the target. These regions are described by ERO using an exponentially decaying potential profile: $V_{\mathrm{mps}}(\mathrm{dz}) = f \cdot V_{\mathrm{sh}} \mathrm{e}^{-\mathrm{dz}/2\lambda_\mathrm{D}} + (f-1) \cdot V_{\mathrm{sh}} \mathrm{e}^{-\mathrm{dz}/r_\mathrm{L}}$, where dz is the distance from the surface, $f \sim 0.1$ for the magnetic field incidence angles in these ASDEX Upgrade experiments and V_{sh} is the total potential drop within the sheath [2, 9].

Impurity Migration in the Outer Divertor

Earlier code-experiment benchmarking has been described in [3–6]. It was shown that the injected hydrocarbons dissociate very fast, so that molecules with a high hydrogen content contribute to the re-deposition only very close to the injection location [4, 6]. The majority of the re-deposition pattern is determined by carbon ions. The observed transport therefore characterizes impurity migration in general. The ions move mainly toroidally along the field lines, but they can also experience cross-field drifts [3]. In the following, we illustrate the poloidal and radial transport, which are important for mixing of materials (e.g. ITER may have poloidally separated C and W tiles in the divertor) and migration from one divertor to another.

Figure 1 shows the modelled carbon ion densities originating from the injection, for forward and reversed field. The densities are integrated over the toroidal length of the simulation volume

(∼40 cm) and the arrows show the locations of the injection valves. To ease the comparison, equal amounts of methane are injected from the two valves in the modelling. One notes that in both field directions, the carbon cloud has a smaller extension at the lower valve, LV, compared to the upper valve, UV. This is due to the shorter ionization length at locations closer to the separatrix, where the density and temperature are higher [4]. The modelled divertor plasma parameters agree with the Langmuir probe measurements in forward field. In reversed field, the modelled target density decays radially faster than the measured density, leading to a factor of 3–5 underestimation compared to measurements at the UV. Consequently, the modelled extension of the UV carbon cloud is likely to be overestimated [4, 6].

Comparison of the clouds in the two field directions reveals the influence of the $\mathbf{E}\times\mathbf{B}$ drifts. In forward field, the $\mathbf{E}_z\times\mathbf{B}$ drift transports impurities towards the separatrix. In reversed field, the $\mathbf{E}_z\times\mathbf{B}$ drift is reversed and transports impurities towards the outer scrape-off layer. However, the net transport is not as large as in forward field, as the impurities are also entrained in the plasma flow that is downwards along the magnetic field lines. Fewer particles cross the separatrix and travel into the private-flux region in reversed compared to forward field. In forward field, the modelling indicates some transport towards the inner target close to the separatrix. A likely explanation for this is the $\mathbf{E}_x\times\mathbf{B}$ drift. In most of the scrape-off layer, $\mathbf{E}_x$ is upwards towards the outer scrape-off layer and produces an $\mathbf{E}_x\times\mathbf{B}$ drift towards the surface. However, in forward field $\mathbf{E}_x$ changes sign at the strike point region, so that close to the separatrix there is transport towards the inner target, on both sides of the separatrix. The modelled effects of $\mathbf{E}\times\mathbf{B}$ drifts have been shown to be in good agreement with the measured local re-deposition patterns, particularly in forward field [4, 6].

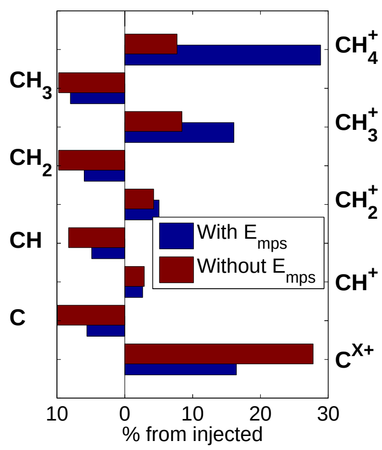

Figure 2: Species returning to the surface from methane injection into the 2009 reversed field plasma (lower valve). See body text for details.

Influence of Magnetic Presheath

The divertor electric field influences not only the transport in the plasma, but also the local re-deposition of impurities. Because of the short dissociation mean-free-path of methane, a large number of hydrocarbon ions are born within the region of magnetic presheath. Here, the strong electric field $\mathbf{E}_{\mathrm{mps}}$ can bring the ions promptly back to the surface. Figure 2 shows the distribution of impinging molecules when the exponentially decaying sheath potential model [2, 9] is used in ERO (default) and when it is excluded, for the case with the shortest ionization mean-free-path. One can see that $\mathbf{E}_{mps}$ increases the fraction of heavy hydrocarbons returning to the surface. Without $\mathbf{E}_{mps}$, the particles travel longer in the plasma and a larger fraction dissociates into carbon before returning to the surface. Hydrocarbons and carbon can have very different sticking behaviour and form different types of surface layers. Therefore, $\mathbf{E}_{mps}$ may influence e.g. fuel retention in the divertor and the potential models should be cross-compared with, for example, detailed particle-in-cell simulations.

Conclusions

The divertor electric field has a large influence on impurity migration in the divertor. In forward field, the $\mathbf{E} \times \mathbf{B}$ drift results in migration towards the private flux region. Close to the separatrix, the modelling indicates transport towards the X-point. In reversed field, transport poloidally along the surface is smaller and towards the outer scrape-off layer. In both field directions, the magnetic presheath $\mathbf{E}$ increases the fraction of hydrocarbons returning to the surface.

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