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ORIGINAL ARTICLE

Contributions to Plasma Physics

Impact of drifts in the ASDEX upgrade upper open divertor using SOLPS-ITER

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Abstract

SOLPS-ITER L-mode-like simulations with the full set of currents and drift velocities activated, and fluid neutrals have been carried out to interpret experimental results obtained in AUG. Drifts are critical to quantitatively reproduce the experimental results; however, simulations without drifts can also reproduce some trends qualitatively. The magnitude and dependence of the peak heat flux onto both targets on the upstream collisionality are, in general, in quantitative agreement within uncertainties with infrared thermography measurements in favourable field direction. The onset of power detachment is observed. In unfavourable toroidal field direction, a more symmetrical inner/outer target solution with regards to the power distribution is predicted, in agreement with experimental observations. However, also in unfavourable toroidal field direction, insufficient power is dissipated in the simulations and therefore $q_{\text{peak, inn}}$ is overpredicted by up to a factor of 4 and $q_{\text{peak, out}}$ by up to a factor of 1.5. The largest contribution to the sources due to radial transport in the energy balance equation is the radial divergence of the energy flux due to $V_{E \times B}$.

KEYWORDS

ASDEX upgrade, divertor detachment, drifts, scrape-off layer, upper single null

1 | INTRODUCTION

Drifts are considered to play a critical role in the Scrape-Off Layer (SOL), particularly impacting divertor plasma transport and the onset of detachment.^[1,2] The onset of detachment is commonly defined as a reduction of both the particle and heat fluxes with respect to their maximum value in an upstream collisionality scan. Understanding and controlling detachment is fundamental for the feasibility of long-term operation of future devices.

The typical flow pattern of the $V_{E\times B}$ drift^[2] for the two directions of the magnetic toroidal field is shown in Figure 1. The toroidal field direction in which the ion $V_{\nabla B}$ drift^[2] points towards the active divertor is defined as *favourable* ($B_T > 0$,

ASDEX-Upgrade Team: see appendix of A. Kallenbach Nucl. Fusion 57 102015 (2017).

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FIGURE 1 Schematic representation of $V_{E \times B}$ and $V_{\nabla B}$ drift direction in upper single null (USN) configuration of AUG for (a) favourable and (b) unfavourable toroidal field direction. The upper disconnected double-null (DDNU) grid for SOLPS-ITER simulations is shown in (c)

Figure 1a). The opposite field direction is *unfavourable* ($B_T < 0$, Figure 1b). They are called favourable and unfavourable with respect to the L-H transition power threshold being lower or higher, respectively. Previous studies of the effect of drifts in different machines and mainly in closed divertors (low neutral escape rate) (AUG, ^[3-6] CMOD, ^[2] JET, ^[7] DIII-D, ^[8] JT60-U^[9]) reported similar observations with respect to the asymmetries of the inner and outer target temperatures and densities. In the favourable field direction, a hotter, less dense outer target with respect to the inner target is usually observed. In the unfavourable field direction, the asymmetry between inner and outer targets is reduced.

To elucidate the underlying physics related to the drifts, the SOLPS (Scrape-Off Layer Simulation Package) ITER code^[10] (commit version: b58ab2b07e415586d013e782af313ed2cdeca74a) has been utilized. SOLPS-ITER solves a set of Braginskii-like fluid conservation equations: continuity and parallel momentum equation for each ion species, electron, and ion internal energy equations and current continuity equation. All ion and fluid neutral species share the same temperature. Fluid neutrals are used in this work.

In a curvilinear coordinate system in which x and y are the poloidal and radial coordinates, respectively, and symmetry is assumed in the toroidal coordinate, z, the most general form of the conservation equation is^[11]:

$$\frac{\partial}{\partial t}A + \frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left(\frac{\sqrt{g}}{h_x}\Gamma_{A,x}\right) + \frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left(\frac{\sqrt{g}}{h_y}\Gamma_{A,y}\right) = S$$
(1)

where A is either the ion density, the parallel momentum, the ion or electron temperatures, or the electric potential; h_x and h_y are the metric coefficients of the coordinate system, $\sqrt{g} = h_x h_y h_z$ is its Jacobian and thus $\sqrt{g} dx dy dz$ is the cell volume.

Equation (1) can be integrated within a desired region of the computational grid (e.g., the divertor) to analyse the relative impact of different components^[12]:

$$s^{y}\Gamma_{x}|_{\partial x} = -\int_{\partial x}\Gamma_{y}ds^{x}|_{\partial y} + \int_{V}S \ dV$$
⁽²⁾

where $s^{[x,y]} = \sqrt{g}/h_{[x,y]} d[y,x]$ are the cell face surfaces.

The diamagnetic flux, Γ^{dia} , is almost divergence free. In SOLPS-ITER, an effective diamagnetic flux, $\widetilde{\Gamma}^{dia}$, corresponding to the nondivergence free part of Γ^{dia} is used in the code instead, so that $\nabla \widetilde{\Gamma}^{dia} = \nabla \Gamma^{dia}$. In this work, however, the physical quantity derived from the plasma solution, Γ^{dia} , will be presented.



2 | SIMULATIONS SETUP

SOLPS-ITER simulations have been carried out for upper single null (USN), unseeded AUG plasmas in low-confinement mode (L-mode) presented in Reference 1. The electron upstream collisionality,^[13]

$$v_e^* = 10^{16} n_e L_{\parallel} / T_e^2$$

will be used as ordering parameter to sort the different upstream conditions of the plasma current and a core density scans.

The proximity between the secondary X-point and the main separatrix (Figure 1c) in these discharges prevents the computational grid from extending further than a few millimetres into the SOL. Such setup is undesirable as a large portion of the power input escapes the computational domain (up to 30% in prelimiary work) and the boundary conditions will have a larger impact than in cases with wider grids. For that reason, a disconnected double-null upper (DDNU) magnetic geometry has been used. The DDNU geometry doubles the physical radial length of the computational domain in the SOL at the outer midplane. The lower outer target has been modified to improve the stability of the simulations by removing a region of highly compressed grid cells.

The SOLPS plasma is composed of three fluid species: deuterium atoms, deuterium ions and electrons. Tungsten is the main impurity species in AUG,^[1] generated by physical sputtering of the plasma facing components material. However, tungsten is assumed to radiate in the core only and thus outside of the computational domain. Kinetic neutrals are not yet considered in this works but will be the next step in future simulations.

The $V_{E \times B}$ and V_{dia} drift are fully activated. The currents associated to the ion-neutral collisions, the perpendicular, and the parallel viscosity are also activated.

The position of the separatrix at the outer midplane extracted from the equilibrium reconstruction is uncertain within a few millimetres. In this work, the upstream profiles are left unshifted for cases with $B_T > 0$ and are shifted by the standard amount of 6 mm for $B_T < 0$. According to the Two-Point Model,^[13] the dependence of the upstream electron temperature, T_e , on the power entering in the SOL, P_{SOL} , is $T_e \propto (P_{Sol}/A_{\parallel})^{2/7}$, where A_{\parallel} is the parallel surface of the flux tube. Because of that, the temperature range considering the minimum and maximum P_{SOL} estimated from the tomographic reconstruction is, for most cases, $T_{e, \text{ sep, min}}/T_{e, \text{ sep, max}} \sim 0.9$. However, for certain plasmas, the ratio might be down to 0.6. Upstream electron separatrix temperatures of 50 eV are expected for L-mode in AUG. However, shifting the profiles in favourable field direction would yield experimental L-mode separatrix temperatures above 100 eV in some cases. On the other hand, unshifted profiles for unfavourable direction would lead to separatrix temperatures below 20 eV in some cases. Integrated Data Analysis^[14] and Thomson Scattering are used for both electron temperature and density in the vicinity of the separatrix and the SOL.

Tomographic reconstructions are used to estimate the radiation within the region of closed flux surfaces and the approximate power crossing the separatrix into the SOL can be calculated with $P_{sep} = P_{heating} - P_{rad}$, $\rho < 0.95$. The electron and ion temperatures at the core boundary are set to values that yield $P_{sep, SOLPS} \simeq P_{sep, exp}$. The electron separatrix density at the outer midplane is controlled with a feedback scheme.

The ambipolar cross-field velocity corresponds to the sum of the $V_{E\times B}$ drift and the diffusive velocity.^[15] This diffusive cross-field transport is assumed to be anomalous and it is prescribed by setting radially varying profiles of the plasma diffusivity, D_{\perp} , and the electron and ion heat diffusivities, $\chi_{e,\perp}$ and $\chi_{i,\perp}$, respectively. Different values of the transport coefficients have been used for each individual experimental plasma, aiming to match the upstream profiles of electron temperature and density ($B_T > 0$, Figure 2a,b, and $B_T < 0$, Figure 2c,d). For each experimental plasma, a sensitivity scan of $\Delta T_{e, \text{ core}} = \pm 25 \text{ eV}$ and $n_{e, \text{ sep, omp}} = \pm 1 \times 10^{18} \text{ m}^{-3}$ has been carried out around an median value, corresponding to the markers in the figures. The sensitivity scan is represented by the error bars in the various figures of this work and it will be used as a proxy for the uncertainties in the simulations. Different sets of D_{\perp} , $\chi_{e,\perp}$, and $\chi_{i,\perp}$ have also been tested (not shown).

The impact of drifts on the low-field side upstream profiles is assessed by summing the radial fluxes above the X-point (Figure 3). In the SOL, the flux due to $V_{E\times B}$ and V_{dia} peaks in the vicinity of the separatrix and it is directed outwards in both toroidal field directions.

In the region of closed flux surfaces, however, the net effect is dependent on the toroidal field direction. Inside the separatrix, it is observed that the combined net effect of $V_{E\times B}$ and V_{dia} implies an outwards pinch in favourable toroidal field direction. This outward-directed flux provides an explanation for the flat density profile for $\rho_{pol} < 0.95$, as smaller gradients are required to accommodate the flux generated by ionization inside the separatrix. Ionization sources might



FIGURE 2 Electron density (a, c) and temperature (b, d) for favourable (a, b, AUG 34311) and unfavourable (c, d, AUG 34312) field direction for $I_p = 0.8$ MA as a function of the normalized magnetic flux, ρ_{pol}



FIGURE 3 Total radial particle flux (black), the portion of the flux due to drifts (red) and the rest of the contributions (green) in medium collisionality in favourable (a) and unfavourable (b) toroidal field directions as a function of the radial distance from the separatrix measured at the outer midplane. Negative values are directed radially inwards while positive values directed radially outwards

be underestimated within the region of closed flux surfaces. In the unfavourable field direction, the net effect results in an inwards pinch, increasing the density gradient. These observations about the density gradients are opposite to the experimental findings. Under similar discharge conditions, steeper density gradients arise in the vicinity of the upstream separatrix of plasmas with favourable field direction with respect to plasmas with the unfavourable field direction. These effects caused the assumed transport coefficients to be different for each field direction.

The direction dependency on the toroidal field direction of the CFS drift-driven flux has been also observed for $I_p = 0.6$, 0.8 and 1.0 MA (not shown).



FIGURE 4 (a-d) Maximum value of heat flux density onto the inner (left column) and the outer (right column) target plates as a function of the outer midplane collisionality in favourable field direction for both core plasma density and plasma current scans. The core density scan (a, b) is performed with a fixed plasma current, $I_p = 0.8$ MA, and the plasma current scan (c, d) is performed with a fixed integrated core plasma density, $\overline{n}_{core} = 2.5 \ 10^{19} \ \text{m}^{-2}$. Black points correspond to experimental values as measured by infrared thermography, red points are the SOLPS-ITER predictions with drifts and orange points are the SOLPS-ITER predictions without drifts activated. Dashed lines connect consecutive points in a given scan. (e, f) Heat flux as a function of the distance from separatrix at the outer midplane for $v_e^* = 10$ case in the favourable field direction (red square in [a, b]). Positive fluxes directed towards targets and positive contributions are sources

3 | RESULTS

3.1 | Favourable toroidal field direction, $B_T > 0$

At $I_p = 0.8$ MA in favourable field direction (Figure 4a,b), with increasing upstream collisionality, the SOLPS-ITER predicted peak heat flux density to the outer target, $q_{\text{peak, out}}$, does not change significantly (increase of 10%) in the low to medium collisionality region (corresponding to low to medium core plasma density). This observation is in quantitative agreement, within experimental and numerical (sensitivity scan) uncertainties, with the reduction of the experimental peak heat flux which is measured with infrared thermography by 15%. At the inner target, $q_{\text{peak, inn}}$ is reduced by a factor of 2, also in quantitative agreement with the experimental observation within uncertainties. In both targets, a significant reduction of the peak heat flux is observed in the medium to high upstream collisionality range. In the simulations, with decreasing I_p and fixed integrated core plasma density, $\overline{n}_{core} = 2.5 \ 10^{19} \ m^{-2}$, (and thus increasing upstream collisionality, Figure 4c,d), both $q_{peak, out}$ and $q_{peak, inn}$ are reduced by a factor of 4, in quantitative agreement with experimental data.

Strong divertor asymmetries are predicted by the simulations: peak heat flux density values at the outer target are up to a factor of three times higher than those in the inner target, which is similarly observed experimentally. This is also the common observation in vertical/closed divertors.

In simulations without $V_{E \times B}$ and V_{dia} enabled, the peaks of the heat flux profiles across both plasma current and core density scans are qualitatively close to both the experimental results as well as the predictions of SOLPS-ITER simulations with drifts. Due to the Shafranov shift and the consequent magnetic field lines compression on the outer side of the closed flux surfaces, more power crosses the separatrix on the outer side than on the inner side, making simulations without drifts somewhat asymmetric.

A detailed analysis of power redistribution and removal is shown for one selected case (Figure 4e,f). Positive fluxes are directed towards the target and positive integrated contributions (Equation (2)) are net sources along a flux tube. The red line corresponds, for $\Delta S < 0$, to the poloidal connection between the divertor targets, and for $\Delta S > 0$, to the power entering from the upstream SOL. In the inner divertor, Figure 4e, most of the power enters from the outer divertor and it crosses into the SOL via radial divergence of radial transport. The largest overall contribution to the divergence of radial transport is due to the $V_{E\times B}$ drift, $Q_{E\times B}$ (not shown). The poloidal flow of $Q_{E\times B}$ is in qualitative agreement with the expected poloidal flow in Figure 1a. Finally, in the vicinity of the separatrix, the divergence of the radial diamagnetic drift-driven energy flux can be up to 50% of $Q_{E\times B}$ (not shown). Power removal in the outer divertor is due to other contributions than radial transport (volumetric processes, plasma-neutral interactions, etc).

3.2 | Unfavourable toroidal field direction, $B_T < 0$

For $B_T < 0$ (Figure 5), it was found experimentally that both divertors are more symmetric with respect to power distribution. Additionally, the upstream collisionality range is small with respect to the scans in the favourable field direction.

In the core plasma density scan (Figure 5a,b), the magnitude and the dependence of the SOLPS-ITER predicted $q_{\text{peak, out}}$ on the upstream collisionality is in quantitative agreement with the experimental observations, within experimental and numerical uncertainties. However, $q_{\text{peak, inn}}$ is overpredicted by up to a factor of 4, due to insufficient power dissipation. In simulations without drifts, the magnitude and trend of $q_{\text{peak, out}}$ is predicted qualitatively well, but the magnitude of $q_{\text{peak, inn}}$ is underpredicted by up to a factor of 3 due to the absence of drift-driven power redistribution among divertors.

Only small variations in the experimental $q_{\text{peak, out}}$ and $q_{\text{peak, inn}}$ are observed across the I_p scan (Figure 5c,d). SOLPS-ITER predicts correctly the trend of $q_{\text{peak, out}}$. However, $q_{\text{peak, inn}}$ is again overestimated by up to a factor of 3 across the I_p scan.

The poloidal energy flux flows, in the private flux region (PFR), from the inner to the outer divertor (Figure 5e,f). The largest contribution to the divergence of radial transport is also due to $Q_{E \times B}$. The contribution of the diamagnetic drift is up to 10% of the total.

4 | CONCLUSIONS

SOLPS-ITER simulations with the full set of available currents and drifts velocities activated and fluid neutrals have been created to interpret the experimental results of L-mode unseeded AUG USN plasmas.^[1] Drifts are important to reproduce quantitatively the experimental results, but simulations without drifts can qualitatively reproduce the trend of the peak heat fluxes onto the target plates for the AUG semiopen upper divertor geometry.

In favourable toroidal field direction, the simulations with drifts quantitatively predict, within experimental and numerical (sensitivity scan) uncertainties, the magnitude of the peak heat flux onto the targets and their dependence on upstream collisionality, including a strong reduction of $q_{\text{peak, out}}$ and $q_{\text{peak, inn}}$, in both plasma core density and plasma current scans.

In unfavourable toroidal field direction, a more symmetrical inner/outer target solution with regards to the power distribution is predicted, in agreement with experimental observations. However, also in the unfavourable toroidal field

direction, insufficient power is dissipated in the simulations and therefore, $q_{\text{peak, inn}}$ is overpredicted by up to a factor of 4 and $q_{\text{peak, out}}$ by up to a factor of 1.5.

The results of the analysis of the integrated sources and sinks are in agreement with theoretical expectations of the $Q_{E\times B}$ flows in the divertor region for both toroidal field directions. The largest contribution to the sources due to radial transport in the energy balance equation is the radial divergence of the energy flux due to $V_{E\times B}$.

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FIGURE 5 (a-d) Maximum value of heat flux density onto the inner (left column) and the outer (right column) target plates as a function of the outer midplane collisionality in unfavourable field direction for both core plasma density and plasma current scans. The core density scan (a, b) is performed with a fixed plasma current, $I_p = 0.8$ MA, and the plasma current scan (c, d) is performed with a fixed integrated core plasma density, $\overline{n}_{core} = 2.5 \ 10^{19} \ m^{-2}$. Black points correspond to experimental values as measured by infrared thermography, red points are the SOLPS-ITER predictions with drifts and orange points are the SOLPS-ITER predictions without drifts activated. Dashed lines connect consecutive points in a given scan. (e, f) Heat flux as a function of the distance from separatrix at the outer midplane for the $v_e^* = 14.5$ case in the unfavourable field direction (red square in [a, b]). Positive fluxes directed towards targets and positive contributions are sources

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