Letter

Effects of a shallow SAS divertor on detachment in KSTAR

Ookjoo Ra\textsuperscript{1}, Kyu Been Kwon\textsuperscript{1}, Livia Casali\textsuperscript{2}, Houyang Guo\textsuperscript{2}, Peter C. Stangeby\textsuperscript{3} and Min Sup Hur\textsuperscript{1,}\textsuperscript{∗}

\textsuperscript{1} Ulsan National Institute of Science and Technology (UNIST), Ulsan, 44919, Korea, Republic Of
\textsuperscript{2} General Atomics, San Diego, CA, United States of America
\textsuperscript{3} University of Toronto, Toronto, ON, Canada

E-mail: mshur@unist.ac.kr

Received 20 July 2020, revised 5 October 2020
Accepted for publication 21 October 2020
Published 2 December 2020

Abstract

For long pulse operation of fusion reactors, it is important to reduce sputter-erosion and power loading of the divertor target by means of plasma detachment. It has been reported that the small-angle-slot (SAS) divertor employed by the DIII-D tokamak can initiate detachment at a relatively low upstream plasma density as it can effectively dissipate heat by concentrating neutrals near the target. Motivated by these findings in DIII-D, we investigated the effects of a SAS-like divertor in KSTAR using SOLPS-ITER simulations without drifts. One remarkable feature revealed by our simulation study is that even a very shallow SAS can lead to a considerably lower heat load on the divertor target than the original flat, open divertor of KSTAR. Deuterium neutrals are concentrated along the divertor separatrix line in the shallow SAS, while deuterium density in the open divertor peaks in the far-scrape-off layer. Furthermore it was found that the neutral density and temperature-drop induced by SAS are both fairly incentive to the depth of the slot. The highest heat dissipation was obtained for a SAS depth of 10.3 cm.

Keywords: divertor, SOLPS, KSTAR, SAS (small angle slot), closure

(Some figures may appear in colour only in the online journal)

1. Introduction

Advanced tokamaks and future reactors require long-pulse operation, which inevitably entails new divertor designs that can significantly reduce the heat flux and temperature at the divertor targets. To suppress the erosion and sputtering of the plasma facing components (PFCs) to acceptable levels, the heat flux and temperature should be maintained under 10 MW m\textsuperscript{-2} and 5 eV \cite{1, 2}.

\footnote{Author to whom any correspondence should be addressed.}

Damage to the PFCs can be reduced effectively by heat dissipation through detachment at the divertor target \cite{3, 4}. Usually detachment is obtained by increasing the upstream density in the scrape-off layer (SOL). However in this case, the core density would also be high, possibly leading to deterioration of confinement of the core plasma. Hence, research on how to trigger detachment at low upstream SOL density, maintaining high quality confinement of the core plasma, is an important issue. From extensive studies of critical factors which determine the upstream density required for the onset of the detachment \cite{5–10}, it has been found that detachment can be affected by the shape of the divertor, PFC material and the magnetic configuration \cite{11–16}.
One direction of optimizing the divertor structures is controlling the path of neutral particles by shaping the divertor. Specifically, divertor closure restricts the paths of neutral particles, confining them near the divertor target and leading to heat dissipation through interactions between the neutral particles and the plasma. The effect of divertor target closure has been validated by a number of numerical simulations as well as experiments in several fusion devices [5–21]. The general conclusion of these studies is that the higher the closure is, the higher the neutral particle density at the divertor target is, and thus detachment can be obtained at lower upstream densities. The high correlation between neutral particle density and electron temperature at divertor targets has been reported in several studies (see [22] and references in [23]).

Based on these results and additional studies [21–24], DIII-D installed a small angle slot (SAS) divertor [25, 26], to obtain more efficient heat dissipation than with conventional divertor shapes. The most critical feature of the SAS divertor is its small angle at the outboard side near the end of the slot. The SAS takes advantage of both closed slot structure and slanted (‘vertical’) target effects, significantly increasing the neutral density in the vicinity of the strike point even at a lower upstream electron density [24–26].

Generally volumetric loss processes which are important in reducing the heat flux to the target (i.e., via detachment), are directly affected by the divertor structure and wall materials as shown in the case of SAS in DIII-D. In this paper, through numerical simulations using the SOLPS-ITER package [27–31] (but without particle drifts), we examined SAS-like divertors in the KSTAR tokamak geometry to identify the factors that dominate the volumetric heat loss near the target (see reference [32, 33] for general characteristics of KSTAR). Due to the limited space around the divertor in KSTAR, the depth of the slot used in our study is much smaller than the original SAS in DIII-D (hence, named SAS-like). Even with a shallow SAS divertor, we obtained a considerable drop in heat flux and temperature near the target. From comparison of the original divertor of KSTAR and the SAS, we have verified that the high neutral deuterium density near the divertor separatrix line plays a critical role in detachment. Interestingly, we discovered that, as long as the slot angles are preserved, the detachment is weakly sensitive to the length of the divertor leg (slot depth).

This paper is organized as follows. In section 2, we describe the setup of the simulation parameters for the SOLPS-ITER code. In section 3, simulation results and analysis are given for comparison between the original and SAS-like divertors in KSTAR geometry. We discuss the effect of the slot depth with other factors held unchanged. In section 4, discussion and conclusions are given.

2. Settings of simulations

The numerical simulations have been performed with the SOLPS-ITER code package. In this code, the multi-fluid plasma transport code B2.5 is coupled to the EIRENE Monte Carlo neutral transport code [30, 31]. B2.5 provides the plasma background on which the neutral trajectories are computed by EIRENE and then EIRENE gives B2.5 the source terms for momentum and energy of neutral particles to be used in the fluid equations of B2.5. Particle drifts are not included in our simulations. The species included in the simulations are plasma species (D, D₂, D⁺ and D²⁺) and all ionization states of sputtered carbon impurity (C, C⁺, C²⁺, C³⁺, C⁴⁺, C⁵⁺, C⁶⁺). Electrons, D⁺ and all the carbon ions are treated by B2.5, while D²⁺ and all the neutral species by EIRENE. We only activate physical sputtering in the simulations, based on the Roth–Bohdansky formula [34], to minimize the impact of carbon radiation on the onset of detachment. This led to small carbon concentration under high density, low temperature divertor conditions. In this way we could study the role of neutral deuterium in detachment onset in the SAS-like divertors. The total recycling rate for D is fixed to R = 1. The density of the main ion species (D⁺) at the interface of core and edge is varied as a boundary condition of the simulation to obtain the scan of outer midplane density (nₑ,comp). For the sheath boundary condition near the target plate, the standard Bohm sheath criterion is used, i.e. \( v || = c_s \). The EIRENE grids are set to be smaller near the top and bottom targets for better resolution of the neutral trajectories near the targets (figure 1).

In the modelling, a computational mesh is constructed based on a lower single null magnetic field configuration of KSTAR as shown in figure 1. The width of B2.5 meshes is 15 mm at the outer midplane, which is wide enough to cover the heat decay length 4–5 mm obtained from simulations. This decay length is comparable to the value typically measured in KSTAR experiments (references [32, 33]). We used the same mesh width for SAS and the original open divertors. The equilibrium magnetic field is provided by the equilibrium fitting code [35]. The lower central divertor of KSTAR is used for the comparison between the original shape and the SAS-like shape. The ion \( \vec{B} \times \vec{\nabla} B \) drift is directed toward the target from the X-point. \( P_{SOL} = 1.2 \text{MW} \) (input power at the inner core boundary of the grid), \( I_p = 0.6 \text{MA} \) and \( B_t = 2.0 \text{ T} \) were used. The list of reactions used in the EIRENE
Figure 2. Density scan of peak values of (a) and (d) $T_e$, (b) and (e) $J_{\text{para}}$ and (c) and (f) $Q_{\text{para}}$ for the original shape (red) and the SAS-like shape (blue). The upper row (a)–(c) represents the data from the inner target, and the lower row (d)–(f) represents the data from the outer target.

simulations can be found in table 1 in reference [36]. In common with most studies using plasma boundary codes, the cross-field transport of particles and heat is assumed to be diffusive with anomalous diffusion coefficients; $D_\perp = 1.0 \, \text{m}^2 \, \text{s}^{-1}$ for particles and $\chi_e(\chi_i) = 1.0 \, \text{m}^2 \, \text{s}^{-1}$ for heat. From these parameters, profiles of L-mode plasmas were formed. Simulations with smaller radial transport coefficients (e.g. $\chi_e(\chi_i) = 0.4 \, \text{m}^2 \, \text{s}^{-1}$, $D_\perp = 0.12 \, \text{m}^2 \, \text{s}^{-1}$) and shorter radial decay length boundary conditions did not alter our results qualitatively. Pumping was not included in order to focus on the effect of the divertor structure. Neutral–neutral collisions were not included either.

3. Simulation results and discussion

3.1. Effect of the SAS-like divertor

Here we compare the original shape and the SAS-like shape of the divertor in KSTAR. The configurations of those two cases have the same magnetic equilibrium and the same SOLPS-ITER input settings except for the shallow slot at the outer divertor in the SAS-like case (see figure 1). The electron temperature ($T_e$), the parallel ion saturation current density ($J_{\text{para}}$) and the parallel heat flux density ($Q_{\text{para}}$) were calculated scanning the electron density at the outer midplane to compare the difference in the onset of detachment (figure 2). Note that $Q_{\text{para}}$, the heat flux parallel to the total magnetic field (toroidal and poloidal) is obtained by multiplying the geometrical factor $\frac{\mu_{\text{eff}}}{\cos \theta}$ to $Q_{\text{perp}}$, which is the energy flux of charged particles normal to the target. Hence $Q_{\text{para}}$ represents the volumetric heat along the field line toward the target. Compared to the SAS in the DIII-D divertor [25, 26], the slot is very shallow. There is not much difference in the inner target (upper row of figure 2) as there is no modification of the inner target. However, from the data of the outer target (lower row in figure 2), it is clear that the SAS-like divertor has advantages over the original divertor. In SAS, the divertor plasma rapidly enters detachment with significant drop in $T_e$ ($<3 \, \text{eV}$) and parallel heat flux density ($Q_{\text{para}}$), followed by the roll-over of the particle flux density ($J_{\text{para}}/e$) at a considerably lower density (by about 35%), compared to the original divertor. Note that the roll-over of the particle flux is usually used as an indicator of divertor detachment in experiments [23], due to a lack of accurate measurements of $T_e$, e.g., by Langmuir probes, in particular, in low temperature plasmas near the detachment. We also have compared the energy flux transported by neutrals toward targets to the energy flux of plasma particles; for open divertors, it is 5 to 10% of $Q_{\text{perp}}$ and 15 to 20% for the SAS-like divertors. The ratio becomes similar for open and SAS-like divertors after the detachment onset.

According to existing research, the lowered onset density of detachment is caused by the increase of volumetric power loss due to increased interaction with neutral particles [10, 22, 23, 36]. Figure 3 shows the molecular deuterium density along the target surface. In the SAS-like divertor (blue line with filled markers), the deuterium density is higher over most of the target compared to the original divertor (red line with filled markers). The temperature (empty markers) is strongly correlated with the deuterium density.
Figure 3. Deuterium density and temperature distribution along the target surface for two different upstream densities at the outer midplane, (a) \( n_{\text{e,omp}} \approx 1.16 \times 10^{19} \text{ m}^{-3} \) and (b) \( n_{\text{e,omp}} \approx 2.34 \times 10^{19} \text{ m}^{-3} \). The filled and empty markers represent the deuterium densities and temperatures, respectively, blue for the SAS and red for the open divertor. The SAS data curves (blue) stop at shorter distance than the open divertor curves (red), because the target surface of the open divertor makes a larger angle to the separatrix line (see figure 6(a)). Number of grid points is the same for both curves.

Figure 4. Neutral deuterium density distribution for two different upstream densities at the outer midplane, (a) and (c) \( n_{\text{e,omp}} \approx 1.16 \times 10^{19} \text{ m}^{-3} \) and (b) and (d) \( n_{\text{e,omp}} \approx 2.34 \times 10^{19} \text{ m}^{-3} \).

Figure 5. 2D contour plots of total radiation (power per unit volume, MW m\(^{-3}\)) for (a) and (b) original divertor and (c) and (d) the SAS-like divertor, for two different \( n_{\text{e,omp}} \).

Both in the original and the SAS-like divertors, with a higher neutral density resulting into a lower electron temperature. The same correlation between the deuterium density on the target and the temperature was found in previous studies [10, 22, 23, 36].

Figure 4 represents the neutral deuterium distribution for upstream densities corresponding to figure 3. It is observed that the neutrals are highly concentrated across the entire target plate for the SAS-like cases. SAS leverages the closed slot structure to enhance neutral build-up inside the slot, and the V-shaped slant target plates near the strike point to direct recycling neutrals toward the strike point from both the common SOL and the private flux region, thus improving plasma cooling across the target plate. In contrast, for the original KSTAR divertor configuration, recycling neutrals are directed away from the strike point with strong leakage of neutrals from the SOL toward the confined plasma, thus reducing power and momentum dissipation in the divertor.

Figure 5 shows the distribution of the radiation for the same parameters as in figures 3 and 4. The power loss by radiation occurs over a larger volume in the SAS-like
Figure 6. (a) The cumulative deuterium density and temperature are calculated along three flux tubes from the X-point to the target; near (red, $r - r_{sep} = 1.25$ mm), mid-apart (green, $r - r_{sep} = 6.18$ mm) and far-apart (blue, $r - r_{sep} = 13.6$ mm) at outer midplane. (b)–(d) Cumulative deuterium density (filled markers, log scale, left ordinate) and temperature (open markers, right ordinate) versus distance from the X-point toward the target along the lines (b) near to the separatrix, (c) mid-apart from the separatrix and (d) far-apart from the separatrix. The tics in the abscissa represent the simulation grid number along the lines, 0 for the X-point and 14 for the target.

The density distribution of neutral deuterium differs not only in the vicinity of the target, but also throughout the entire divertor volume. Figure 6 shows the cumulative deuterium density and temperature along three magnetic flux tubes from the X-point to the target. Note that, since the temperature drop due to volumetric power loss is a cumulative effect, the integrated $n_{D_2}$ can be more informative than $n_{D_2}$ itself in understanding the relation between $D_2$ and $T_e$. As can be seen, there is a correlation between the density of deuterium and the temperature change; along the line near to the separatrix (red line in figure 6(a)), the neutral deuterium density of the SAS is larger than the original divertor and hence the temperature is significantly lower (figure 6(b)). In contrast, along the mid-apart (green in figure 6(a)) or far-apart (blue in figure 6(a)) from the separatrix, there is no difference in the neutral deuterium densities between the SAS and the original divertor, hence the temperature is comparable (figures 6(c) and (d)).

Figure 6 shows that the beneficial effect of SAS, i.e. the higher neutral density resulting in lower temperature, extends from the X-point to the target. Furthermore, such an effect of SAS is limited to the near-SOL where the heat and particle fluxes are concentrated. Hence the result also implies that potentially the SAS effects could be more evident in scenarios with narrow SOL width (i.e. at high plasma current and/or in H-mode) than for the broad SOL (i.e. at low current and/or in L-mode).
3.2. Effect of the slot depth

A set of simulations were performed changing the depth of the slot, while maintaining the angle between the slot facets and the magnetic separatrix (∼ 43°). Figure 7(a) shows three different slot depths used in the simulations. The parallel current (figure 7(b)) on the outer target increases as the slot depth (hence, the leg length) decreases, but interestingly, the onset of roll-over (hence, detachment) occurs at a similar upstream density in all three SAS-like cases. Also the temperature and the heat flux are not affected by the depth of the slot (figures 7(c) and (e)) and remain considerably lower than in the original divertor. As can be seen in figure 7(d), the neutral deuterium density is almost the same for all the slot depths (and significantly higher than for the open divertor). This simulation data strongly suggests that the slot angles are more important than the slot depth for the onset of detachment. This finding implies an advantage of SAS from the cost point of view: an easier access to divertor detachment might be obtained just by a minimal change of the divertor target shape, with no need of a deep slot structure. Note that the depth of the shortest slot in figure 7 is about 5.6 cm, which increases the leg length (i.e. distance from the X-point to the target) just by 10% from the original divertor.

4. Conclusion

In summary, using SOLPS-ITER simulations without particle drifts, we studied the effects of a SAS-like divertor in KSTAR. We observed that with the SAS-like divertor, detachment is accessed at lower plasma density at the outer midplane by 35% in agreement with a similar work at DIII-D [37]. The concentration of deuterium neutrals around the separatrix line was higher in the SAS-like divertor than in the open divertor, while there is little difference far from the separatrix. In addition, we found that detachment is very weakly sensitive to the depth of the slot. These observations suggest that the target shape and angle to the field line at the strike point are crucial elements to achieve high neutral density around the separatrix line. This result is compatible with the conclusion in references [38, 39], where the optimal divertor structure is obtained from an optimization algorithm.

In addition to divertor geometry, particle drifts can also affect the onset of divertor detachment [40–45] and will be, therefore, included in future modelling. Another aspect that should be investigated is the sensitivity of the detachment in SAS to a small change in the outer strike point location [37] and the effects of SAS on core behavior [45, 46] in KSTAR. In addition, the change of heat flux transported by neutral particles and radiations toward the target for different divertors should be analyzed. These issues are under investigation as a next step of our research.

Acknowledgments

M.S.H. was supported by the National Research Foundation of Korea (Grant Nos. NRF-2016R1A5A1013277 and NRF-2020R1A2C1102236). O.R., K.B.K., M.S.H. are supported by National Research Foundation of Korea.
References

[1] Stangeby P.C. and Leonard A.W. 2011 Obtaining reactor-relevant divertor conditions in tokamaks Nucl. Fusion 51 063001
[2] Stangeby P.C. 2000 The Plasma Boundary of Magnetic Fusion Devices (Bristol: Institute of Physics Publishing)
[3] Chan V.S., Costley A.E., Wan B.N., Garofalo A.M. and Leuer J.A. 2015 Evaluation of CFETR as a Fusion Nuclear Science Facility using multiple system codes Nucl. Fusion 55 023017
[4] Zohm H. et al 2013 On the physics guidelines for a tokamak DEMO Nucl. Fusion 53 073019
[5] Garofalo A.M. et al 2014 Progress in the physics basis of a Fusion Nuclear Science Facility based on the advanced tokamak concept Nucl. Fusion 54 073015
[6] Tobita K. et al 2009 Compact DEMO, SlimCS: design progress and issues Nucl. Fusion 49 075029
[7] Kawashima H., Shimizu K. and Takizuka T. 2007 Development of integrated SOL/divertor code and simulation study of the JT-60/JT-60SA tokamaks Plasma Phys. Control. Fusion 49 S77
[8] Kukushkin A.S., Pacher H.D., Janeschitz G., Loarte A., Coster D.P., Matthews G., Reiter D., Schneider R. and Zhogolev V. 2002 Basic divertor operation in ITER-FEAT Nucl. Fusion 42 187
[9] Kawashima H., Shimizu K., Takizuka T., Asakura N., Sakurai S., Matsuoka M. and Fujita T. 2008 Design study of JT-60SA divertor for high heat and particle controllability Fusion Eng. Des. 83 1643–7
[10] Casali L., Eldon D., Boedo I.J., Leonard T. and Covele B. 2020 Neutral leakage, power dissipation and pedestal fueling in open vs closed divertors Nucl. Fusion 60 076011
[11] Kallenbach A. et al 2015 Partial detachment of high power discharges in ASDEX Upgrade Nucl. Fusion 55 053026
[12] Loarte A. 2001 Effects of divertor geometry on tokamak plasmas Plasma Phys. Control. Fusion 43 R183–224
[13] Neu R. et al 2003 The ASDEX Upgrade divertor IIb—a closed divertor for strongly shaped plasmas Nucl. Fusion 43 1191–6
[14] Theiler C. et al 2017 Results from recent detachment experiments in alternative divertor configurations on TCV Nucl. Fusion 57 072008
[15] Harrison J.R. et al 2019 Progress toward divertor detachment on TCV within H-mode operating parameters Plasma Phys. Control. Fusion 61 065024
[16] Fil A., Lipschultz B., Moulton D., Dudson B.D., Février O., Myatra O., Theiler C., Verhaegh K. and Wensing M. 2020 Separating the roles of magnetic topology and neutral trapping in modifying the detachment threshold for TCV Plasma Phys. Control. Fusion 62 035008
[17] Horton L.D. et al 1999 The effect of divertor geometry on divertor and core plasma performance in JET J. Nucl. Mater. 266–269 160–7
[18] Bosch H.-S. et al 1999 Effect of divertor geometry on boundary and core plasma performance in ASDEX Upgrade and JET Plasma Phys. Control. Fusion 41 A401
[19] Schneider R., Bosch H.S., Neuhauser J., Coster D., Lackner K. and Kaufmann M. 1997 Divertor geometry optimization for ASDEX Upgrade J. Nucl. Mater. 241–243 701–6
[20] Lipschultz B., Goetz J.A., Hutchinson I.H., Labombard B., McCracken G.M., Takase Y., Terry J.L., Bonoli P. and Golovato S.N. 1996 Variation of the divertor geometry in Alcator C-mod Proc. 19th Int. Conf. Fusion Energy (7 - 11 October 1996, Montreal, Canada ) (Vienna: IAEA) p 425 https://inis.iaea.org/search/search.aspx?orig_q=RN:28063132
[21] Casali L., Sang C., Moser A.L., Covele B.M., Guo H.Y. and Samuel C. 2018 Modelling the effect of divertor closure on detachment onset in DIII-D with the SOLPS code Contrib. Plasma Phys. 58 725–31
[22] Stangeby P.C. and Sang C. 2017 Strong correlation between D2 density and electron temperature at the target of divertors found in SOLPS analysis Nucl. Fusion 57 056007
[23] Stangeby P.C. 2018 Basic physical processes and reduced models for plasma detachment Plasma Phys. Control. Fusion 60 044022
[24] Sang C., Guo H.Y., Stangeby P.C., Lao L.L. and Taylor T.S. 2017 SOLPS analysis of neutral baffling for the design of a new divertor in DIII-D Nucl. Fusion 57 058043
[25] Guo H.Y., Sang C.F., Stangeby P.C., Lao L.L., Taylor T.S. and Thomas D.M. 2017 Small angle slot divertor concept for long pulse advanced tokamaks Nucl. Fusion 57 044001
[26] Guo H.Y. et al 2019 First experimental tests of a new small angle slot divertor on DIII-D Nucl. Fusion 59 086054
[27] Braaks B.J. 1987 A multi-fluid code for simulation of the edge plasma in tokamaks Next European Torus (NET) Report EUR-FUS/XII-80/87/68 NET Garching
[28] Schneider R. Deiter D., Zehrfeld H.P., Braams B., Baelmans M., Geiger J., Kastelewicz H., Neuhauser J. and Wunderlich R. 1992 B2-EIRENE simulation of ASDEX and ASDEX-Upgrade scrape-off layer plasmas J. Nucl. Mater. 196–198 810–5
[29] Schneider R., Bonnin X., Borraas K., Coster D.P., Kastelewicz H., Reiter D., Rozhansky V.A. and Braams B.J. 2006 Plasma edge physics with B2-EIRENE Contrib. Plasma Phys. 46 3–191
[30] Bonnin S. et al 2015 The new SOLPS-ITER code package J. Nucl. Mater. 463 480–4
[31] Bonnin X., Dekeyser W., Pitts R., Coster D., Voskoboynikov S. and Wiesen S. 2016 Presentation of the new SOLPS-ITER code package for tokamak plasma edge modelling Plasma Fusion Res. 11 1403102
[32] Bak J.G. et al 2014 SOL parameters, and particle and heat fluxes at divertor targets from electric probe measurements in KSTAR J. Kor. Phys. Soc. 65 1232–8
[33] Lee H.H. et al 2017 Thermographic studies of outer target heat fluxes on KSTAR Nucl. Mater. Energy 12 541–7
[34] Bohdansky J., Roth J. and Bay H.L. 1980 An analytical formula and important parameters for low-energy ion sputtering J. Appl. Phys. 51 2861
[35] Lao L.L., John H.S., Stambaugh R.D., Kellman A.G. and Pfeffer W. 1983 Reconstruction of current profile parameters in J-2 density and electron temperature at the target of divertors Nucl. Fusion 9 583–32
[36] Casali L., Covele B.M. and Guo H.Y. 2019 The effect of neutrals in the new SAS divertor at DIII-D as modelled by SOLPS Nucl. Mater. Energy 19 337–43
[37] Dekeyser W., Reiter D. and Baelmans M. 2014 Divertor target shape optimization in realistic edge plasma geometry Nucl. Fusion 54 073022
[39] Dekeyser W., Reiter D. and Baelmans M. 2014 Automated divertor target design by adjoint shape sensitivity analysis and a one-shot method J. Comput. Phys. 278 117–32

[40] Chankin A.V., Corrigan G., Groth M. and Stangeby P.C. 2015 Influence of the $E \times B$ drift in high recycling divertors on target asymmetries Plasma Phys. Control. Fusion 57 095002

[41] Aho-Mantila L. et al 2017 Assessment of SOLPS5.0 divertor solutions with drifts and currents against L-mode experiments in ASDEX Upgrade and JET Plasma Phys. Control. Fusion 59 035003

[42] Rozhansky V., Kaveeva E., Senichenkov I., Sytova E., Veselova L., Voskoboynikov S. and Coster D. 2018 Electric fields and currents in the detached regime of a tokamak Contrib. Plasma Phys. 58 540–6

[43] Kaveeva E. et al 2020 SOLPS-ITER modelling of ITER edge plasma with drifts and currents Nucl. Fusion 60 046019

[44] Du H. et al 2020 Manipulation of $E \times B$ drifts in a slot divertor with advanced shaping to optimize detachment Nucl. Fusion 60 126030

[45] Casali L., Osborne T.H., Grierson B.A., McLean A.G., Meier E.T., Ren J., Shafer M.W., Wang H. and Watkins J.G. 2020 Improved core-edge compatibility using impurity seeding in the small angle slot (SAS) divertor at DIII-D Phys. Plasmas 27 062506

[46] Sang C.F., Guo H.Y., Stangeby P.C., Wang H.Q., Wang L. and Wang D.Z. 2020 SOLPS analysis of changes in the main SOL of DIII-D associated with divertor detachment vs attachment and closure vs openness Nucl. Fusion 60 056011