1. Introduction

Particle and energy fluxes to the plasma facing components (PFCs) during edge localized modes (ELMs) are expected to unacceptably shorten the PFCs lifetime in ITER. In order to understand the consequences of kinetic effects of ELMs to PFCs, PARASOL simulations have been carried. Initial 1-D simulations showed that both the in/out asymmetry of divertor parameters before ELMs as well as the magnitude of the ELM energy loss itself have an influence on the in/out asymmetry of the ELM divertor fluxes with the total energy deposited at the divertor being larger at the hotter/lower recycling divertor. The role of the thermoelectric current ($I_{\text{SOL}}$) has been studied with further 1-D simulations in which decreasing $I_{\text{SOL}}$ leads to an increase of the ELM power deposition at the colder/higher recycling divertor but the degree of in/out asymmetry is smaller than in the experiment. PARASOL-2D simulations have been carried out to study the effects of plasma drifts on the asymmetries of ELM energy and particle transport. It shows that for the favourable $\nabla B$ direction the ELM energy flux is predominantly deposited at the inner divertor while for the unfavourable $\nabla B$ direction it is at the outer divertor, which is in agreement with experimental findings.

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1-D and 2-D approximations [3]. Initial simulations with PARASOL 1-D [4] had shown that both the in/out asymmetry of divertor parameters between ELMs (due to different recycling conditions at the two divertors) as well as the magnitude of the ELM energy loss itself have an influence on the in/out asymmetry of the ELM divertor power fluxes, although the total energy deposited by the ELM tends to be biased towards the divertor with lower recycling between ELMs (outer divertor for the $\nabla B$ direction favourable for H-mode access), which is contrary to experimental observations. This was identified to be due to the fact that large thermoelectric currents circulate between the two divertors during the ELMs in the simulations. Although at the inner divertor the product of ion flux and plasma temperature ($T_i + T_e$) during the ELM is largest (due to the higher recycling), the sheath transmission coefficient at the outer divertor is typically a factor of 2-8 times higher than at the inner divertor during the ELM, due to the strong thermoelectric currents, which leads to the ELM power flux at the outer divertor to be largest [4]. To understand the role of thermoelectric currents on ELM power deposition asymmetries, PARASOL 1-D simulations have been carried out where one divertor target (the inner one, higher recycling between ELMs) is assumed to be floating so that thermoelectric current flow during ELMs is considerably reduced,
which is found to affect the in/out ELM divertor power flux asymmetry in the direction expected, as described in Sec. 3.

The PARASOL 2-D code was previously used for the modelling of kinetic effects on the SOL flow pattern for stationary plasmas including plasma drifts [3,5]. This has been further extended to include ELMs by the development of a simple ELM model in PARASOL 2-D. We have considered two magnetic configurations for plasmas in a single null poloidally diverted geometry: one with the favourable ion $\nabla B$ drift direction for H-mode access (so called “normal” $\nabla B$) and the other with unfavourable ion $\nabla B$ drift direction for H-mode access (so called “reversed” $\nabla B$). In these 2-D simulations other effects that introduce in/out divertor asymmetries between ELMs, associated with impurity radiation, different divertor recycling conditions, etc., are not yet included.

In the next section, the simulation models and parameters of the PARASOL 1-D and 2-D codes are described. Simulation results are presented in Sec. 3, and Sec. 4 consists of a summary of the results and required further work. Additional previous studies with PARASOL 1-D and 2-D can be found in [6–9]. Kinetic modelling for the SOL plasma between and during ELMs in existing fusion devices and ITER with other PIC codes are described. Simulation results are presented in Sec. 3, and Sec.4 consists of a summary of the results and required further work. Additional previous studies with PARASOL 1-D and 2-D can be found in [6–9]. Kinetic modelling for the SOL plasma between and during ELMs in existing fusion devices and ITER with other PIC codes are described in [10–13].

### Table 1 Modelling parameters for ITER simulations in PARASOL 1-D between ELMs and at the ELMs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal magnetic field (T)</td>
<td>5.3</td>
</tr>
<tr>
<td>Major/Minor radius (m)</td>
<td>6.2/2.0</td>
</tr>
<tr>
<td>Poloidal length L (m)</td>
<td>33</td>
</tr>
<tr>
<td>SOL width (m)</td>
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</tr>
<tr>
<td>Mass ratio $m_i/m_e$</td>
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</tr>
<tr>
<td>Separatrix density ($m^{-3}$)</td>
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</tr>
<tr>
<td>Separatrix temp. (eV)</td>
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</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
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</tr>
<tr>
<td>Hot source region</td>
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</tr>
<tr>
<td>Pitch angle</td>
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</tr>
<tr>
<td>Recycling temp. (eV)</td>
<td>2.5</td>
</tr>
<tr>
<td>Recycling Ratio “in/out”</td>
<td>0.5/0.0, 0.99/0.0</td>
</tr>
<tr>
<td>ELM temp. (keV)</td>
<td>1.0, 2.5, 5.0</td>
</tr>
<tr>
<td>ELM duration $\tau_{\text{ELM}}$ (µs)</td>
<td>200</td>
</tr>
<tr>
<td>ELM width $L_{\text{ELM}}$</td>
<td>0.27L</td>
</tr>
</tbody>
</table>

2. Simulation Models and Parameters

#### 2.1 1-D ELM simulation with floating divertor

The 1-D SOL-divertor plasma simulated by the PARASOL code [3] is bounded by two divertor plates located at $x = 0.0$ and 1.0, where the $x$ direction corresponds to the poloidal direction for the SOL-divertor region in a tokamak. We consider a plasma with one species of singly charged ions (mass $m_i$ and charge $e$) and electrons (mass $m_e$ and charge $-e$), for simplicity. The orbits of ions are fully traced, while guiding-centre orbits are followed for electrons. The anomalous transport is simulated with a Monte-Carlo random-walk model. The effects of Coulomb collisions are simulated by using a binary collision model [6]. The electric field $E_x = -\partial \phi/\partial x$ is determined by Poisson’s equation (Eq. (1)). Ion and electron densities, $n_i$ and $n_e$, are calculated self-consistently with the PIC method of the area-weighting scheme. The magnetic field $B$ is taken to be constant in the SOL-divertor with a pitch of $\Theta = B_y/B$, whose value is set 0.25 in this study and intersects the divertor plates obliquely. Table 1 shows the modelling parameters of the ITER simulations for plasma conditions between the ELMs and during the ELMs. The value of the separatrix density ($10^{20} m^{-3}$) has been chosen artificially high to obtain very asymmetric plasma conditions between the two divertor plasmas with PARASOL to study the effect of divertor asymmetries between ELMs on the particle and power asymmetries during the ELMs. This density value was required because the recycling and radiative losses modelled in PARASOL are simplified compared to those in 2-D fluid simulation codes [14]. The inter-ELM plasma conditions between the two divertors were varied by adjusting the recycling coefficient $R_{\text{rec}}$ for the particle and radiative losses so that the inner divertor was colder and denser than the outer one which is in agreement with experimental observations for “normal” $\nabla B$. Two levels have been studied Mid-recycling $R_{\text{rec}} = 0.5$ and High recycling $R_{\text{rec}} = 0.99$. In this paper we show the results for High recycling only, the reader is referred to [4] where the High recycling and Mid-recycling cases were compared. The choice of 0.99/0.0 in/out divertor recycling levels represents an example of an extreme asymmetry in/out divertor recycling asymmetry. The level of 0.99 is typical of divertor conditions in ITER over a large density range, i.e. the core ionization source due to neutral escape from the divertor is typically less than 1% of the divertor ion flux in ITER [15]. The ELMs are modelled by the addition of a number of particles ($N_{\text{ELM}}$) with a temperature ($T_{\text{ELM}}$) in the SOL for a time interval ($\tau_{\text{ELM}}$) where the values of these parameters are adjusted to reproduce the expectations for ITER [1].

The electrostatic potential $\phi$ is determined by the one dimensional Poisson’s equation as

$$-\partial^2 \phi/\partial x^2 = (e/\epsilon_0)(n_i - n_e), \tag{1}$$

where $\epsilon_0$ is the permittivity of vacuum. In the simulations we model the (inner) floating divertor by applying a difference of electric potential $\Delta \phi (\phi_{\text{in}} = \Delta \phi, \phi_{\text{out}} = 0)$ be-
tween the two divertors as boundary condition. The SOL-averaged electric current $J_x$ is thus given by

$$J_x = eL^{-1} \int dx (n_i v_{xi} - n_e v_{xe}) / N_{av},$$  

(2)

where $v_{xi,xe}$ are the velocities of the charged particles and $N_{av}$ is the SOL-averaged ion density. To reduce the thermoelectric current a potential difference $\Delta \phi$ is applied at the inner divertor to obtain

$$\Delta \phi = C_v \int_{\Delta t} dt (J_x - J_0),$$  

(3)

where the input parameters on the strength of floating potential $C_v$ and the desired thermoelectric current $J_0$ are adjusted from the modelling results between ELMs by imposing $C_v = 0.1, J_0 = 0$ and are kept constant between the ELMs and during the ELMs in order to get the thermoelectric currents reduced during the ELMs, while $\Delta \phi$ is varied in time. $\Delta \phi$ in Eq. (3) is integrated over the interval $\Delta t$, which is the time-step used in this modelling.

2.2 2-D ELM simulations on opposite X-point positions

The tokamak plasma is simulated in a cylindrical coordinate system $(r, \theta, z)$ inside a rectangular region in the $r$-$z$ plane surrounded by rectangular walls, $-a_w < r - R_0 < a_w$ and $-b_w < z < b_w$, where $R_0$ is the major radius of the vessel centre (Fig. 1). A regular rectangular grid is adopted for the PIC modelling and axisymmetry is assumed. The magnetic field for the poloidally diverted configurations considered $B = (B_r, B_\theta, B_z)$ is produced by the combination of a core plasma current channel and two divertor coil currents. The plasma minor radius $a$ is defined at the midplane separatrix, and the aspect ratio is given as $A = R_0 / a$. The toroidal magnetic field $B_\theta$ is proportional to $1/R$, and the pitch of magnetic field $\Theta$ is set as $|B_r / B_\theta|$ is provided at the outer mid-plane separatrix as input parameter. The orbits of ions are fully traced and solved with the leap-frog method, while guiding-centre orbits are followed for electrons by using the predictor-corrector method. Poisson’s equation in the two dimensional cylindrical coordinates is approximated by the finite difference equation, and is solved by the tri-diagonal matrix algorithm (TDMA) in the $r$ direction and the fast Fourier transform (FFT) algorithm in the $z$ direction. The electrostatic potential, including the sheath potential at the plasma-wall boundary, is fully simulated. The rectangular wall boundary is considered to be electrically conductive, and the wall potential is set $\phi = 0$. A source of hot particles is injected in the core plasma to simulate plasma heating. In this study, a uniform source of hot particle is considered for the core plasma region inside the magnetic separatrix (−$a < r < a$ at the midplane). Ions and electrons with a temperature $T_0 = T_{e0} = T_{i0}$ are supplied uniformly in this region with hot ion and electron pairs being born at the same spatial position.

The number of ions in the simulations $N_i$ is $10^8$ and the number of spatial cells $M_x \times M_z$ is $320 \times 512$ and the size of each cell is 0.25 both for $r$ and $z$ direction and the normalized length is determined as $\Delta l = \Delta t * v_{th,e}$, where $\Delta t$ is the normalized time-step and $v_{th,e}$ is the electron thermal velocity. The mass ratio $m_i / m_e$ is chosen as 400 to save computation time. The aspect ratio $A$ is set as 5.4 and the pitch of the magnetic field $\Theta$ is 0.2 at the outer mid-plane separatrix determining the parallel connection length $L_{||} = 2 \pi a / \Theta$. The typical ratio of the ion Larmor radius to plasma minor radius in these simulations is $\rho_{Li} / a = 0.02$ ($\rho_{Li}$: ion Larmor radius at hot ion temperature $T_{i0}$;  $a$: plasma minor radius) and various values of plasma $L_{||}/\lambda_{mfp}$ have been considered from collisionless to collisional plasmas, where $\lambda_{mfp}$ is the electron-electron collisional mean free path. Regarding the ELM parameters, two normalized ELM durations have been considered $\tau_{ELM}/\tau_{i0} = 0.16$ (short) and 2 (long) where $\tau_{i0}$ is the SOL parallel ion transit time $\tau_{i0} \sim L_i / C_i$ ($C_s$ is sound speed). The resulting ELM energy losses for the main plasma are very small $\Delta W / W_{sep} < 1\%$, as required for controlled ELMs in ITER [1]. It should be noted that, due the scaling of the ratio of plasma drift velocities to the sound speed with the size of the modelled system, the effects of drifts in our simulations (which have a much smaller size than the real plasma) are augmented with respect to the experiment [13] and thus only the relative (not quantitative) effects of drifts can be modelled with our approach.

The anomalous transport is simulated with a Monte-Carlo random-walk model. A spatial displacement perpendicular to $B$, $\Delta x_{anom}$, is added for every time step in the motion equations both on electrons and ions. The isotropic
displacement is given by a Gaussian random number \( g \), and its mean square is
\[
< \Delta r_\text{anom}^2 > = D_\text{anom} \Delta t, \quad (4)
\]
\[
\Delta r_\perp = \Delta r_\text{anom} / \Delta t = (D_\text{anom} / \Delta t)^{0.5} g. \quad (5)
\]
The ELM modelling in this study is implemented by multiplying Eq. (5) by a constant \( k_\text{ELM} \) in a selected region of the plasma and added as an additional displacement caused by the ELM to both electrons and ions to simulate the expulsion of particles by the ELM. The parameters chosen in the cases \( \tau_\text{ELM} / \tau_{\text{eff}} = 0.16 \) (short) and 2 (long) are \( k_\text{ELM} = 0.5 \) and 0.05 respectively. The region over which \( k_\text{ELM} \) is introduced leads to particles entering SOL in the outer midplane region as shown in Fig. 1.

### 3. Simulation Results

#### 3.1 Effect of thermal electric currents on ELM in/out deposition asymmetries

Figure 2 shows the time evolution of particle flux \( \Gamma_\perp \) and thermoelectric SOL current \( (I_{\text{SOL}}) \) for a Type-I ELM with total energy \( E_\text{ELM} = 20 \text{MJ} \) and \( T_\text{ELM} = 5 \text{keV} \) for ITER for in/out asymmetric divertor plasma conditions between ELMs \( (n_{\text{in}} = 3.1 \times 10^{19} \text{m}^{-3}, \ T_{\text{in}} = 1.5 \text{eV} \) and \( n_{\text{out}} = 2.7 \times 10^{19} \text{m}^{-3}, \ T_{\text{out}} \sim 100 \text{eV}, \) in/out recycling ratio 0.99/(0.0). Figures 2(a) and 2(b) are results with fixed potential boundary condition that allow thermoelectric current flow \( (\phi_{\text{in}} = \phi_{\text{out}} = 0) \), and Figs. 2(c) and 2(d) are for the case in which the inner divertor is floating \( (\phi_{\text{in}} = \Delta \phi, \phi_{\text{out}} = 0) \). The simulations allowing thermoelectric current \( I_{\text{SOL}} \) showed [4] that the particle flux is higher at the inner divertor before the ELM and increases faster when the ELM starts leading to a larger power being initially deposited at the inner divertor (in the ion channel). However, at the time of the peak power deposition both inner and outer power fluxes are similar and, correspondingly, the total heat load deposited in the two divertors by the ELM. In agreement with previous simulations the largest fraction of the ELM energy is deposited by ions \([3, 10, 11]\). Because of the asymmetry of the temperature between ELMs at the divertor, \( I_{\text{SOL}} \) appears between the inner and the outer divertor (Fig. 2(b)) and this leads to more electrons reaching the outer divertor target (Fig. 2(a)) and to a larger electron heat flux there. This compensates the initial asymmetry caused by the ion flux and leads to an overall symmetric ELM energy deposition at the two divertors when \( I_{\text{SOL}} \) flows in the SOL. When the boundary condition is modified so that the inner divertor is floating the electron & ion particle fluxes are similar on both divertors (Fig. 2(c)) whilst the value of the ion fluxes at the two divertors remain as in the case with \( I_{\text{SOL}} \). This leads to a higher power flux to be deposited at the higher recycling divertor in agreement with the high ion flux there as is in this case electron and ion fluxes at each of the two divertors is the same due to the absence of net SOL current. It should be noted that, while these simulations include the effect of in/out divertor recycling asymmetries leading to different ion fluxes and neutrals densities at the two divertors during the ELM, they do not include the effect of charge-exchange (CX) between the outflowing ions with the incoming neutrals which have been found to be important in other studies[12]. A model for CX implemented in PARASOL is being presently in the process of verification to enable us to assess the effects of CX in our simulations.

The ratio of asymmetric inner/out divertor ELM energy deposition (Fig. 3 (top)) and power flux deposition (Fig. 3 (bottom)) shows that the effects of thermoelectric current are to increase the balance towards the inner divertor. The magnitude of the effect is larger for the ELM power flux asymmetry than for the ELM energy flux asymmetry and for the latter the larger effects are found for smaller energy losses \( \Delta W_{\text{ELM}} \). The level of in/out ELM power flux deposition asymmetry can be as high as 4 but, the in/out ELM energy deposition asymmetry typically obtained is not larger than 1.2 and thus lower than the factor of 2 typically found in experiment. In these simulations we have considered various combinations of the energy and quantity of ions/electrons expelled into the SOL by the main plasma during the ELM which correspond to the same total ELM energy loss \( \Delta W_{\text{ELM}} \). The range covers an electron/ion temperature of 5 keV (expected pedestal temperature in ITER for \( Q = 10 \) operation [2]) to 1 keV. Correspondingly, the total number of electrons/ions expelled by the ELM has been adjusted to obtain the same \( \Delta W_{\text{ELM}} \) for all the ELM-expelled ion/electron temperatures. This reproduces, in a simplified way, the well-established experimental observation that, depending on plasma conditions,
ELM energy losses can be dominated by plasma conduction (loss of fewer and more energetic ions/electrons) or convection (loss of a larger number of particles of lower energy)[16].

3.2 Asymmetric heat load dependence on ion ∇B drift direction

Figure 4 shows the time evolution of the modelled power (top) and energy (bottom) fluxes at the inner and outer divertors during an ELM modelled with PARASOL-2D. Figures 4(a)-(b) correspond to the case which the ion ∇B drift direction is “reversed” and Figs 4(c)-(d) correspond to the “normal” ion ∇B direction. The time τi1 is the time at which the electron power flux is highest at the outer target and τi2 is the one for the inner target. τe1 is the time when the ion heat power flux is highest at the outer target and τe2 is the same for the inner target case. A fast-time-scale transient behaviour is observed in the electron flux qE for both ion ∇B drift directions, τe1 ∼ τELM at outer target and τe2 ∼ 2τELM at inner target which is determined by the ELM particle expulsions geometry losses concentrated at the outer midplane closest to the outer target. The slow-time-scale transient behaviour observed in the ion power flux, on the contrary, depends strongly on the direction of the ∇B drift: τi1 ∼ 15τELM ∼ 2.4τi∥ for the “reversed” ∇B and τi2 ∼ 30τELM ∼ 4.8τi∥ for the “normal” ∇B drift directions.

Figure 5 presents the time evolution of the power flux asymmetry qin/qout in PARASOL 2-D runs for the two ion ∇B directions with a minimum qin/qout ∼ 0.2 at τi1 for the “reversed” ∇B case and qin/qout ∼ 2.7 at τi2 for the “normal” ∇B case. The resultant ELM energy deposition asymmetry is Ein/Eout ∼ 0.3 for “reversed” ∇B case and Ein/Eout ∼ 1.5 for “normal” ∇B case. These trends are qualitatively consistent with experimental findings of Ein/Eout ∼ 1.0 - 2.0 for “normal” ∇B case Ein/Eout ∼ 0.5 - 1.0 for “reversed” ∇B[17].
The in/out ELM power flux asymmetry changes drastically with the ion $\nabla B$ drift direction. The in/out asymmetry $q_{in}/q_{out}$ is $\sim 0.1$ for “reversed” $\nabla B$ and $q_{in}/q_{out}$ is $\sim 2.7$ for “normal” $\nabla B$.

4. Summary and Further Work

The effects of divertor recycling and thermoelectric currents on the in/out divertor ELM power flux load asymmetries have been modelled with PARASOL 1-D, and the effect of the $\nabla B$ direction on divertor ELM power flux asymmetries in 2-D magnetic configurations has been modelled with PARASOL 2-D. Thermoelectric currents have a strong influence on the ELM power flux asymmetry and enhance the ELM power flux load at the divertor which is hotter/lower recycling between ELMs. Reducing thermoelectric currents increases the ELM power flux at the divertor which is colder/higher recycling between ELMs but the power flux/energy load in/out asymmetry during ELMs remains lower than the usual factor of 2 found in experiments for the “normal” $\nabla B$ direction in which the inner divertor is colder/higher recycling than the outer one between ELMs. The direction of ion $\nabla B$ drift direction has a very strong effect on the ELM heat power flux in/out divertor asymmetry with deposition to the inner divertor being dominant for “normal” $\nabla B$ and to the outer divertor for “reversed” $\nabla B$. This is robust to modelling assumptions (ELM duration and plasma collisionality) and in qualitative agreement with experimental measurements.

The complete picture including the direct effects of the $\nabla B$ direction during ELMs and the effects of the $\nabla B$ direction on in/out divertor asymmetries between ELMs requires inclusion of a recycling model in PARASOL-2D, which is progress.

Acknowledgments

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