Modelling of the effects of divertor recycling conditions and toroidal field direction on divertor power and particle flux asymmetries between and during ELMs with PARASOL for COMPASS-like plasmas

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1. Introduction

Particle and energy fluxes to the plasma facing components (PFCs) during edge localized modes (ELMs) are expected to unacceptably shorten the lifetime of PFCs in ITER [1]. Non-linear MHD simulations of ELMs for ITER plasmas, assuming a fluid model for the edge parallel transport, have been made [2]. However, ELM transport in the ITER SOL-divertor plasma is collisionless given the high pedestal plasma temperature [3]. In order to understand the consequences of kinetic effects on the power and particle fluxes to PFCs between ELMs and during ELMs, particle simulations with PARASOL [4, 5] have been carried out for COMPASS H-mode plasmas [6, 7] with two directions of the toroidal field.

2. Simulation Model and Parameters

The magnetic equilibrium of a COMPASS discharge has been used to define the computational mesh used in the modelling and two directions of the magnetic field have been considered: ion $B\times\nabla B$ direction towards the X-point (Normal) and opposite to the X-point (Reversed). The description of the two modelled H-mode COMPASS plasmas is summarized in Table 1. Besides magnetic equilibrium, the main PARASOL-2D inputs are the separatrix plasma density and temperature and the anomalous diffusion coefficient, which is adjusted to reproduce the measured inter-ELM profiles of the divertor plasma parameters, and the recycling coefficient at the divertor R_{recyc}, which accounts for local divertor ionization. D_{anom} = 0.004 m^2/s is used in these COMPASS simulations to approach the very small divertor power flux width of λ_{q} < 1 mm (mapped to the midplane) measured in these H-modes. To model the ELM the value of the anomalous diffusion coefficient is increased by a factor of up to 2500 for 200 μs over the edge plasma region in the radial and poloidal plane (typically 15° around the outer midplane and $0.8 < \psi < 1.1$ in normalized magnetic flux). This leads to a decrease of the plasma energy by the ELM of $\Delta W_{\mathrm{ELM}} \approx$ 100 - 260 J, corresponding to $\Delta W_{\mathrm{ELM}}/W \approx$ 1-3 % and in a similar range to the experiment.

3. Simulation Results

The measured inter-ELM divertor ion flux (I_{sat}, with probe effective area of 2.8 mm^2) and T_e by Langmuir probes for the plasmas modelled in Fig. 1 show that the direction of the field affects both the relative location of the maximum I_{sat} and T_e at the inner and outer divertors as well as their in/out asymmetry. Reversing the direction of the field in COMPASS shifts the T_e profile inwards in minor radius compared to I_{sat} and decreases I_{sat} and increases T_e at the inner divertor. PARASOL simulations for a range of R_{recyc} shown in Fig. 2 for the two directions of the field reproduce the radial shift of the I_{sat} and T_e profiles with the direction of the field, with the magnitude of this shift depending on the values of R_{recyc} and D_{anom} used in the modelling. On the contrary, PARASOL simulations show more in/out symmetric I_{sat} profiles when the direction of the field is reversed due to a decrease of the outer divertor I_{sat}, which is opposite to the experiment. The reasons for this discrepancy are not understood; they could be due to the fact that the two experimental plasmas with different field directions have different levels of additional heating while the PARASOL simulations are done for constant separatrix density and temperature for both field directions. The measured and modelled divertor power fluxes are shown in Fig. 3 and 4 for R_{recyc} = 0.3, respectively. Reversing the direction of the field broadens the inner and outer divertor power deposition profiles by ~ 1.5 both in experiment and modelling ($\lambda_{qout}^{Normal\text{-}mp}$ = 0.43 mm and $\lambda_{qout}^{Reversed\text{-}mp}$ = 0.64 mm). It should be noted, however, that even assuming D_{anom} = 0.004 m^2/s in PARASOL, the modelled λ_q is a factor of 2-3 larger than in experiment and that the broadening at the outer divertor depends on the value of R_{recyc}. Similarly the in/out divertor power flux asymmetry in PARASOL is influenced by both field direction and R_{recyc} so that a universal trend of the in/out power asymmetry inter-ELMs with field direction cannot be identified.

Table 1. COMPASS plasma discharges modelled with PARASOL 2D

Shot Number	#14021	#14041
Mode, Heating	H, Low NBI heating	H, no NBI heating
B_{t}, Ion $B\times\nabla B$ direction	-1.38 (T), Normal	+1.38 (T), Reversed
I_{p}	+290 (kA)	-220 (kA)
n_{e}	9.0*10^{19} (m^{-3})	6.5*10^{19} (m^{-3})
$\Delta W_{\mathrm{ELM}}/W$	7.5 %	3%

PARASOL simulations of COMPASS ELMs have been performed for both field directions and a range of anomalous transport enhancements corresponding to a range of ΔW_{ELM}. The temporal evolution of the inner and outer divertor power fluxes in the electron and ion channels for ELM simulations with the two directions of the field is shown in Fig. 5. The main effect of the field direction is to reverse the divertor ion power flow, which changes from being dominant at the inner divertor for normal field to being dominant at the outer divertor for forward field. As the ion channel is the dominant one for the total ELM energy flow in the PARASOL simulations, this leads to a change of ELM energy deposition in-out asymmetry from E_{in}/E_{out} = 2 for normal field to E_{in}/E_{out} = 0.25 for reversed field, which is weakly dependent on ΔW_{ELM}, as shown in Fig. 6. Experimentally, it is also found that E_{out}

increases with respect to E_{in} when the field is reversed, as also shown in Fig. 6. However, the COMPASS experiments with forward field show that ELM energy fluxes are dominant to the outer divertor for normal field, which is opposite to PARASOL predictions and previous experimental evidence from JET and ASDEX-Upgrade [8]. An interesting finding of the PARASOL simulations is that for the same ELM modelling assumptions (same D_{anom} enhancement) $\Delta W_{ELM}^{Normal}/\Delta W_{ELM}^{Reversed}$ ~ 1.5-2, as shown in Fig. 6. This is a common experimental observation (reversed field discharges have smaller ΔW_{ELM} and larger ELM frequencies that normal field ones) and points towards a link between ELM energy losses and SOL energy transport, which is affected by drifts as shown in this paper.

4. Summary and conclusions

The effects of divertor ∇B direction on steady-state and ELM power fluxes at the inner/outer divertors have been modelled with PARASOL for COMPASS plasmas. The experimental trend for the relative shift of I_{sat} vs. T_e with field direction can be reproduced, showing that this results from drifts. Similarly, the broadening of I_{sat} and $q_{||}^{corr}$ profiles for reversed field are reproduced for specific R_{recyc}. PARASOL results show that in/out divertor asymmetries are not only affected by drifts but also by R_{recyc}, so that universal trends cannot be extracted. PARASOL results for ELM energy deposition show that reversing the field leads to a lower ΔW_{ELM} and E_{in}/E_{out}, which also is seen in COMPASS plasmas. However, ELM energy deposition to the outer divertor is always dominant in COMPASS, unlike in PARASOL results and JET-ASDEX-Upgrade experiments. Further 2-D PARASOL simulations of COMPASS plasmas will be performed to study the role of drifts, recycling and thermoelectric currents on divertor stationary and ELM power fluxes.

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5. References

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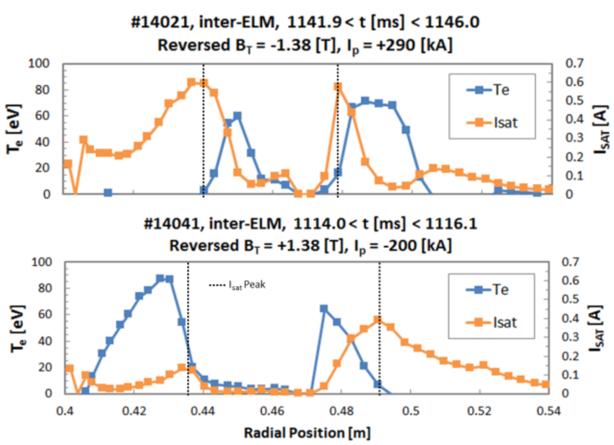

Figure 1. Radial profiles T_e and I_{sat} between ELMs in COMPASS plasmas #14021 and #14041. The field direction modifies the alignment of T_e and I_{sat} profiles. Reversing the field decreases I_{sat} at the inner divertor and increases T_e. Reversing the field increases the width of the I_{sat} profile by ~ 4 times at the outer divertor and by ~2 times the inner one.

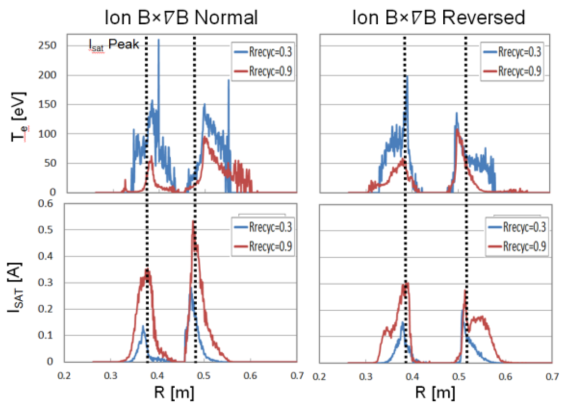

Figure 2. Radial profiles of T_e and I_{sat} between ELMs modelled with PARASOL both for Normal and Reversed field. Higher R_{recyc} decreases T_e and increases I_{sat} both for Normal and Reversed field, as expected. The relative shift of I_{sat} vs. T_e as well the I_{sat} broadening when reversing the field direction follows the experimental trend.

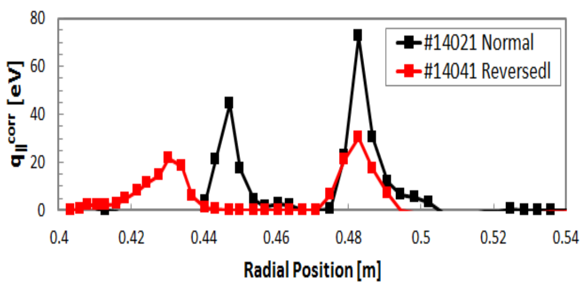

Figure 3. Radial power flux profiles between ELMs in COMPASS plasmas #14021 and #14041 ($q_{||}^{corr} = \gamma T_e I_{sat}$, $\gamma = 7$). The power flux is larger at the outer divertor for both field directions but the in-out ratio and λ_q change with field direction (wider and more in/out balanced power fluxes for reversed field).

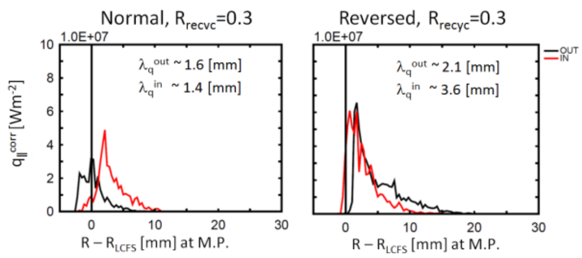

Figure 4. PARASOL modelled inner and outer divertor power fluxes mapped to the midplane. The increase of λ_q at both inner and outer divertor with reversed field is reproduced with R_{recyc} = 0.3. The modelled values of λ_q even with $D_{anom} = 0.004\ m^2s^{-1}$ are a factor of 2-3 larger than in experiment.

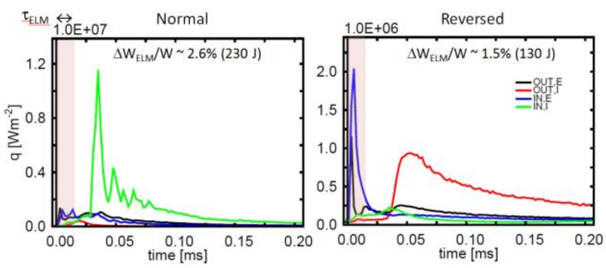

Figure 5. PARASOL modelled time evolution of the electro/ion power flux at inner/outer divertors during an ELM for normal/reversed field. The total ELM energy loads are larger at the inner divertor for normal field and at the outer one for reversed field, following the changes to the in/out ion power flow.

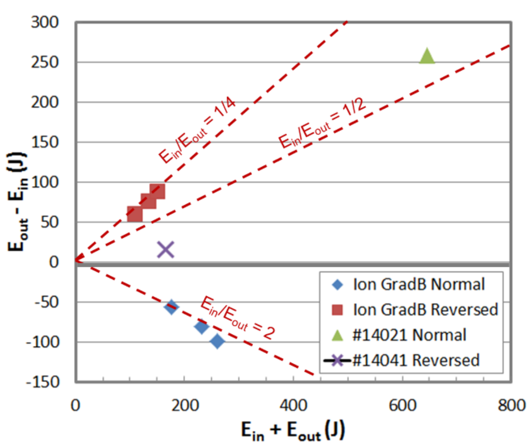

Figure 6. Difference of the ELM energy deposited at the outer and inner divertors for PARASOL modelling and COMPASS plasmas as a function of total ELM energy loss. The field direction has a strong effect on the in/out divertor asymmetry of deposited ELM energy increasing at the outer divertor when the field is reversed.