Kinetic Modelling of Divertor Fluxes during ELMs in ITER

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1 Introduction

Particle and energy fluxes to the plasma facing components (PFCs) during uncontrolled edge localized modes (ELMs) are expected to unacceptably shorten the PFC lifetime for high Q scenarios in ITER on the basis of empirical extrapolations from existing experiments [1]. Non-linear MHD modelling of these particle and energy fluxes carried out for ITER has shown that some aspects of such empirical extrapolations, such as the scaling of the broadening of the ELM power footprint at the divertor with ELM energy loss, may not apply at the ITER scale [2]. However, the robustness of these findings is questionable because the particle and energy transport along the field lines in these MHD simulations is modelled in a fluid approximation and for low recycling divertor conditions. This is not applicable at ITER during an ELM in ITER because this transport is essentially collisionless given the high plasma temperatures in the pedestal plasma and where the divertor is expected to operate in high recycling/semi-detached divertor conditions. In order to understand the consequences of kinetic effects on ELM energy and particle transport, modelling of typical edge plasma conditions during (and between) ELMs in ITER has been carried out with the 1-D PARASOL particle-in-cell code [3].

2 Simulation Models and Parameters

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 x direction corresponds to the poloidal direction for the SOL-divertor region in a tokamak. The magnetic field B is taken to be constant in the SOL-divertor with a pitch of $\Theta = B_x/B$, 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 Type I 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 model in PARASOL are simplified compared to those in 2-D fluid simulation codes [4]. The inter-ELM plasma conditions between the two divertors were varied by adjusting the recycling coefficient for the particle and radiative losses (two levels are shown in this paper Mid and High recycling) so that the inner divertor was colder and denser than the outer one as seen in experiments. The ELMs are modelled by the addition of a given number of particles (N_{ELM})

with a given temperature (T_{ELM}) in the SOL for a given time (τ_{ELM}) where the values of these parameters are adjusted to reproduce the expectations for ITER [1].

Toroidal magnetic field (T)	5.3	Z_{eff}	1.5
Major/Minor radius (m)	6.2/2.0	Hot source region	0.24 L ~ 0.76 L
Poloidal length L (m)	33	Divertor region	0.0 L ~ 0.24 L and 0.76 L ~ 1.0 L
Sol width (m)	$2.0\ 10^{-2}$	Recycling temperature. (eV)	2.5
Pitch angle	$2.5\ 10^{-1}$	Recycling Ratio “in/out”	0.5/0.0 (Mid), 0.99/0.0(High)
Mass ratio m_i/m_e	$3.67\ 10^{3}$	ELM temperature (keV)	1.0, 2.5, 5.0
Separatrix density (m^{-3})	$1.0\ 10^{20}$	ELM duration τ_{ELM} (μs)	200
Separatrix temperature (eV)	300	ELM width L_{ELM}	0.27 L

Table. 1 Modelling parameters for ITER simulations between ELMs and at the ELMs.

3 Simulation Results

Fig. 1 shows the time evolution of particle flux Γ_x, heat flux q and total energy heat for a Type I ELM with total energy E_{ELM} = 20 MJ and T_{ELM} = 5 keV in ITER for the case with very asymmetric divertor plasma conditions between ELMs ($n_{in} = 3.1\ 10^{21}\ m^{-3}$, T_{in} =1.5 eV and $n_{out} = 2.7\ 10^{19} m^{-3}$, T_{out} ~ 100 eV) corresponding to the high recycling in/out ratio (0.99/0.0). 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. It should be noted that most of the ELM power is deposited by the ions, in agreement with previous simulations [3].

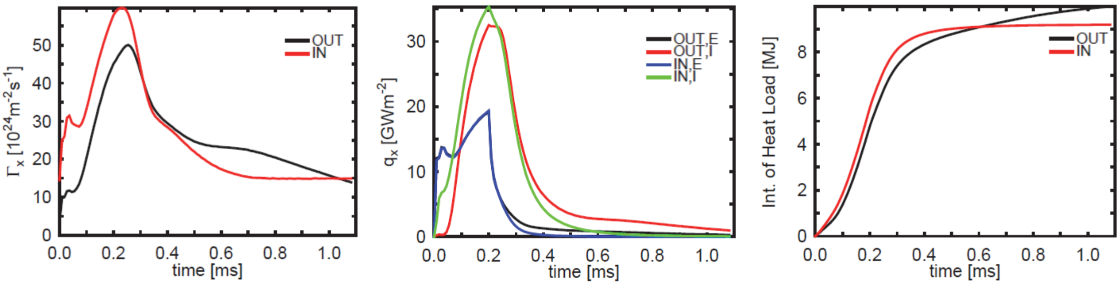

Figure 1. Time evolution of particle flux, heat flux and total heat load to the two divertors for a Type I ELM of 20 MJ and T_{ELM} = 5 keV in the asymmetric high recycling case. The label “OUT” refers to the outer divertor, “IN” to the inner divertor, “E” to the electron and “I” to the ion channels.

In order to investigate how the magnitude of the ELM and the characteristics of the particles lost by the ELM influence the timescale and asymmetry ELM divertor power deposition we have carried two scans. In one we have scanned the size of the ELM energy loss by varying the temperature of the particles lost in the ELM and in the other by varying the number of particles loss by the ELM. Fig. 2.a shows the results for the case in which the temperature of the ELM particles is varied T_{ELM}= 5, 2.5, 1.0 keV decreasing the ELM energy loss by 5. Fig.

2.b shows the results for the case in which the number of particles lost by the ELM is varied (for constant T_{ELM}= 5 keV) decreasing the ELM energy loss by 5 as well.

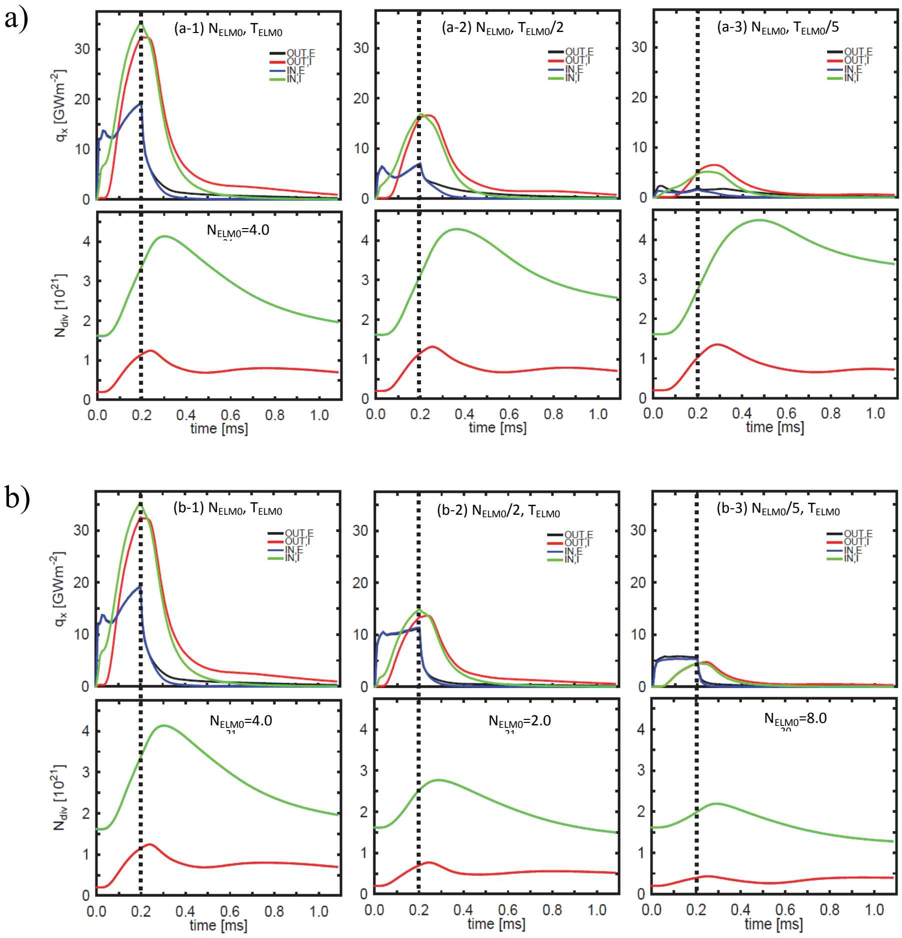

Figure 2. **(a)** Time evolution of the heat flux q deposited by the ELM at the inner and outer divertor targets and the number of particles in in/out divertor regions during the ELM for ELMs with a total particle loss of N_{ELM0}= 4.0 10^{21} and T_{ELM} = 5, 2.5, 1.0 keV. **(b)** Time evolution of the heat flux q deposited by the ELM at the inner and outer divertor targets and the number of particles in in/out divertor regions during the ELM for ELMs with temperature T_{ELM} = 5 keV and particle loss N_{ELM} = 4.0 10^{21}, 2.0 10^{21}, 8.0 10^{20}. The plasma conditions before the ELM correspond to the high recycling case.

For the cases in Fig. 2.a the number of particles lost by the ELM is larger than those at the divertor before the ELM, In this case the reduction of T_{ELM} leads to a liner reduction of the divertor power fluxes, a similar ratio to the electron and ion power fluxes (dominated by the ion channel) and to the lengthening of the ion divertor power pulse as expected from the longer ion transit time. For the cases in Fig. 2.b, the number of particles lost by the ELM is larger than those at the divertor before the ELM for the large ELM energy loss but the opposite is true for the smaller ELM energy losses. The decrease of ELM energy loss by reducing the number of ELM particles causes also a decrease of the divertor power fluxes but in this case the ratio of the powers lost in the electron and ion channels vary. For large ELM particle losses the ion channel is dominant while for the smaller losses the electron channel is dominant. This is consistent with the capability of the plasma at the divertor to carry power through the sheath when the electron temperature increases during the ELM (higher ion flux at the inner divertor before the ELM) and has the potential to shorten the ELM divertor power deposition time when the ion transient time is smaller than τ_{ELM}.

Despite these clear differences there is not a large asymmetry between the peak divertor fluxes at the inner and outer divertors and we find the total ELM heat load is largest at the outer divertor. In fact, for the smallest ΔW_{ELM} the amount of energy going to the inner divertor is lowest which is surprising in view of the arguments regarding the higher capability of the inner divertor plasma to carry ELM power fluxes in the electron channel mentioned above. The reason for this is that the electron and ion fluxes to the divertors have a complex time history with strong electron current flowing between the two divertors which compensate the differences expected because of the pre-ELM ion fluxes between the two divertors. This is shown in Fig. 3 in which the evolution of both electron and ion particle fluxes during the ELM at the two divertor is displayed. The inner divertor has a larger ion flux during the ELM and this (in the absence of a net SOL current) would lead to a higher power flux. However during the ELM a strong thermo-electric current is established which reduces the electron flux at the inner divertor and increases it at the outer one. As a consequence of this the power flux at the outer divertor is larger despite a much smaller ion flux (consistent with the lower recycling conditions of the outer divertor). The effective sheath transmission coefficient ($\gamma = q_{div}/[G_{ion\text{-}div} \times T_{e\text{-}iv}]$) calculated from the PARASOL simulation remains low for the inner divertor (with a value of ~ 7.5 after 1 ms from the ELM occurrence) while that at the outer divertor reaches values of ~ 40 at the time of maximum electron current flow.

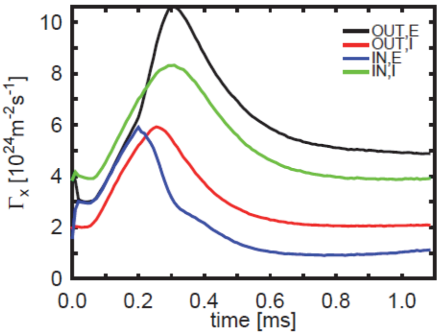

Figure 3. Time evolution of the inner and outer divertor electron and ion fluxes particle for mid-recycling conditions before the ELM and for ΔW_{ELM} = 4MJ (corresponding to T_{ELM}=1 keV) showing the complex time history of the electron and ion fluxes to the inner divertor during the ELM. A large thermo-electric current exists during the ELM which flows from the outer to the inner divertor.

4. Summary

Particle and power fluxes to the inner and outer divertor during Type I ELMs in ITER have been simulated with the PARASOL code for asymmetric divertor recycling conditions before the ELM. Results show that most of the power flux is deposited by ions at the divertor when $N_{ELM} > N_{div}$, whereas ions and electrons deposit comparable heat flux when $N_{ELM} \leq N_{div}$. Despite these changes the ELM heat load is largest at the outer divertor due to the establishment of thermo-electric currents between the divertor during the ELM. Results will be used for non-linear MHD simulation of ELMs in ITER with JOREK.

5. References

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