**Topic: EX-D**

# ELM transport in the JET scrape-off layer

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Edge Localised Modes (ELMs) are universally recognised as one of the greatest threats to the viability of ITER and future fusion power plants based on the tokamak concept. They are plasma relaxations driven by MHD modes and are thought to originate in the steep pressure gradient region of the edge transport barrier characteristic of H-mode plasmas. In ITER, extrapolations from JET predict that Type I ELMs in the $Q_{DT}$ = 10 baseline scenario will expel between 3-8% of the 350 MJ plasma stored energy, depositing energy fluxes of 0.6 – 3.4 $MJm^{-2}$ on the divertor targets [1]. Only at the lowest values of this energy range would the subsequent target erosion be tolerable. Of late, concerns are being raised not just for the divertor targets, where most of the ELM energy is intercepted, but also for the main chamber walls to where ELM power fluxes are now known to extend.

The mechanisms governing the ELM origin location and non-linear evolution within the H-mode pedestal and the subsequent cross-field propagation within the scrape-off layer (SOL) remain the subjects of keen debate. Once in the SOL, however, the thermal energy within the filament is removed predominantly by parallel losses to divertor targets, a process which is better understood but which is nevertheless complex, comprising both kinetic and fluid effects. This contribution aims to demonstrate how experiments and modelling at JET are significantly advancing our understanding of the ELM SOL parallel transport, providing many of the key elements required for an integrated, quantitative treatment of the ELM energy fluxes and their subsequent consequences for plasma-wall interaction.

Infra-red thermography is extensively employed for divertor target measurements at JET and has recently been complemented by a unique new wide angle view of the main chamber wall surface. Such measurements are technically challenging due to the fast transient nature of the ELM and the presence of thin surface layers, which can differ radically from surface to surface. Taking proper account of this reveals that ELMs deposit energy preferentially (~ factor 2) in the outer target at low pedestal collisionality ($\nu^*$) but that this ratio inverts in favour of inner target energy deposition (up to ~ factor 3) with rising $\nu^*$.

These target plate measurements of the ELM heat flux transient, in combination with fast triple Langmuir probe data, have provided the first known experimental evidence for

* See Appendix of J.Pamela et al., Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura) IAEA, Vienna (2004)

strong variations in the sheath heat transmission coefficients during the ELM. The magnitude and temporal variation of these variations are in good agreement with new kinetic simulations of parallel dynamics in the JET Type I ELMing SOL using the BIT1+ particle-in-cell (PIC) code. Pre-ELM values of the heat transmission coefficients and parallel heat flux limiters extracted from the PIC runs are in excellent agreement with classical expectations. At the ELM, the simulated target energy flux increases promptly due to electron loss, reaches a plateau as negative space charge in the sheath accumulates, then increases further following the arrival of the bulk ion pulse. This is manifest by order of magnitude increases in heat flux limits and transmission coefficients with the amplitude of this rise scaling linearly with the pedestal temperature. Neglecting these transient effects in 2D fluid Monte-Carlo simulations can lead to the target heat fluxes being underestimated by factors of up to 4 for 1 MJ ELMs on JET, with obvious implications for extrapolation to heat loads expected on ITER. In addition, the distribution of ion energies at the targets can be strongly weighted towards higher energies, with consequences for ELM divertor target erosion. Efforts are underway at JET to include the time dependent sheath transmission and heat flux limiters derived from the kinetic simulations into ELM modelling using the EDGE2D and SOLPS5 code packages. To achieve this efficiently requires a simplified parameterisation of the coefficient variations, an exercise which has been facilitated by the development of a new transient model of ELM filament energy evolution due to parallel losses, including both kinetic and fluid treatments [2]. Parametric expressions for the heat transmission coefficients are being derived using this model on the basis of extremely favourable comparisons with the full PIC simulations.

This same transient model matches a wide range of ELM observations in the JET SOL. Divertor target heat fluxes monitored during main chamber limiter-separatrix gap scans are used to derive SOL radial temperature profiles during the ELM, yielding $\lambda_{Ti}/\lambda_{Te} \sim 3$, showing that ions in the ELM filament lose energy more slowly than electrons as it propagates radially (consistent with the lower parallel ion mobility). The model closely matches both these inferred characteristic lengths and direct measurements of ion energies in the far SOL obtained with a retarding field analyser (RFA) probe reciprocating into the edge plasma at the top low-field-side of the poloidal cross-section [3]. This data clearly shows that ions, convected by the ELM to the main walls, arrive there with energies up to 50% of those characteristic in the pedestal plasma. Meanwhile, the ratio of currents to RFA sensors facing into the outer and inner divertors is strong evidence for a poloidally localised, outboard midplane origin for the JET Type I ELM. In the divertor, the out/in target heat flux ratios are also reproduced by the model, at least for low pedestal collisionalities. The effect of local increases in divertor radiation provoked by the ELM, now accessible with the upgraded JET bolometry system, will be discussed in the context of the increased in/out ELM heat flux asymmetry observed as density rises – an effect not reproduced by the model.

A second fast probe head, specifically adapted for fluctuation measurements, detects the ELM as a turbulent phenomena, comprising a wavetrain of pulses consistent with plasma filaments released simultaneously at multiple toroidal locations from a rotating pedestal. Each pulse contains a rich substructure, likely a consequence of the main filaments disintegrating and stretching as they propagate radially. Radial particle fluxes carried by the ELM are measured to increase with increasing ELM size, as do the ELM filament cross-field velocities, observations supported by divertor thermography showing that the fraction of the pedestal ELM energy loss deposited in the divertor decreases as the ELMs become larger. Recent direct measurements of the ELM-main chamber wall heat fluxes confirming this finding will be presented and compared with estimates from the transient model.

[1] A. Loarte et al., Phys. Plasmas **11** (2004) 2668
[2] W. Fundamenski, R. A. Pitts, Plasma Phys. Control. Fusion **48** (2006) 109
[3] R. A. Pitts et al., Nucl. Fusion **46** (2006) 82