A comparison of the spatial structure of ELMs at the mid-plane in ASDEX Upgrade and MAST

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The edge transport barrier associated with H-mode plasmas gives rise to steep edge pressure gradients, which can drive instabilities known as Edge Localised Modes (ELMs) [1]. So called type-I ELMs result in the sudden release of 5-15 % of the stored energy in a short amount of time (100-1000 μs), which results in large heat fluxes to plasma facing components [2][3]. Understanding the parameters that determine the temporal and spatial energy deposition of ELMs and hence their impact on plasma facing materials is an important area of research for future devices like ITER. In this paper, detailed measurements of the radial extent and spatial structure of type-I ELMs observed on ASDEX Upgrade and MAST will be presented together with a simple model for ELM energy losses.

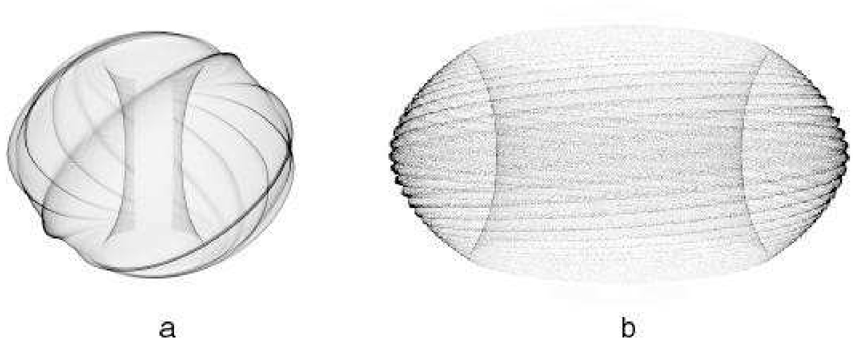

Figure 1 An image simulation of an ELM composed of 10 equally spaced filaments with a width perpendicular to the field line of 5cm and aligned along the q_{95}~4 field line for a) MAST and b) ASDEX Upgrade.

Filamentary enhancements of visible light are observed on photographic images of the plasma obtained during ELMs on MAST [4]. Comparisons with simulations show that these filaments are consistent with following field lines at the outboard edge of the plasma. These filaments have a toroidal mode number of ~ 10 and a width perpendicular to the field line of 5-8cm. The result of such a simulation is shown in Figure 1a. The filaments are well separated at the outboard mid-plane due to the magnetic configuration of a Spherical Tokamak. If the same structures were produced during an ELM in a conventional aspect ratio tokamak such as ASDEX Upgrade they would look like the simulation shown in Figure 1b. Due the shallower pitch angle and the magnetic configuration the filaments appear much closer together, which makes resolving the filaments more difficult. In addition it is only possible to obtain a limited view of the edge of the plasma. However, images obtained during ELMs of the outboard edge of the ASDEX Upgrade plasma using a fast (10 - 30 μs exposure time) colour camera have shown clear filament like structures, consistent with the simulation, with a poloidal extent of 5 - 8 cm and separated poloidally by 10 - 15 cm. On both MAST and ASDEX Upgrade the filaments have a similar width perpendicular to the field line in the flux surface of ~ 5-8 cm.

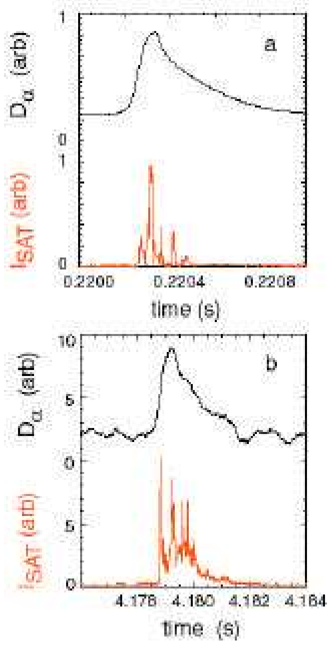

Figure 2 The D_α signal and the I_{SAT} observed at the outboard mid-plane during a single ELM on a) MAST and b) ASDEX Upgrade.

Further evidence for the filamentary structure of ELMs comes from a study of the ion saturation current (I_{SAT}) observed during an ELM at the mid-plane manipulator. Figure 2a and b shows a plot of I_{SAT} and the divertor D_α during a single ELM on MAST and ASDEX Upgrade respectively. As can be seen, the I_{SAT} shows four or more distinct features during a single ELM. Each peak lasts for ~ 15 (60) μs and they are separated by 60 (110) μs on MAST (AUG). If the I_{SAT} peaks are analysed assuming that they are due to filaments rotating with the plasma edge then it would indicate that the filaments have a width in the toroidal direction of 15cm (60) cm on MAST (AUG). The difference is due mainly to the difference in pitch angle on the two devices. In fact the width of the filament perpendicular to the field line would be ~ 7-10 cm on both devices roughly consistent with the size of ~5-8 cm obtained from the visible images.

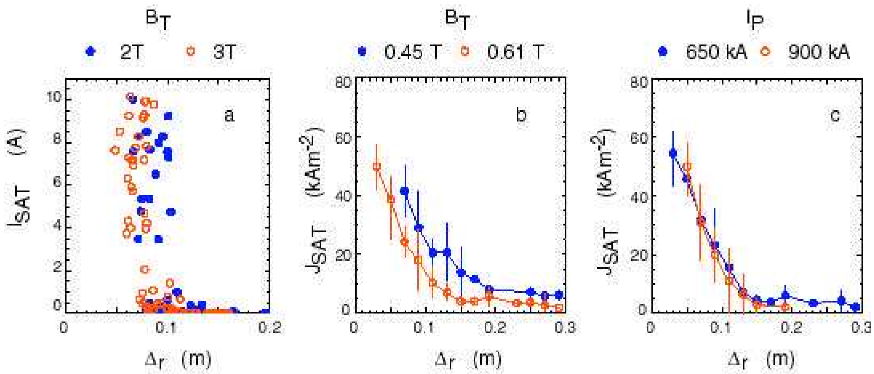

Figure 3 The ion saturation current as a function of distance from the plasma edge for a) ASDEX Upgrade at two toroidal fields, b) MAST at two toroidal fields and c) MAST at two plasma currents.

The ion saturation current has been measured as a function of distance from the plasma edge (Δ_r) at the outboard mid-plane on MAST and ASDEX Upgrade. Figure 3a and b shows a plot of the peak I_{SAT} as a function of Δ_r for ASDEX Upgrade and MAST for shots with different toroidal magnetic fields (B_T). Considerable I_{SAT} values can be observed to extend to Δ_r ~10 cm on ASDEX Upgrade and ~20 cm on MAST. The radial extent also appears to be larger on both devices at smaller toroidal field. In order to determine whether the change in radial efflux is due to the magnetic field or to q_{95}, a set of discharges were performed on MAST at a constant B_T of 0.54 T but different plasma current (650 and 900 kA) corresponding to q_{95} = 5.5 and 4.0 respectively. As can be seen from Figure 3c the radial extent for these discharges is effectively the same suggesting that it is the toroidal magnetic field that affects the radial extent of the ELM.

The delay (Δt) between the rise in D_α emission and the first peak in the I_{SAT} distribution combined with the distance between the probe and plasma edge (Δ_r) has been used to calculate a pseudo-radial velocity ($V_r=\Delta_r/\Delta t$). The mean value of this radial velocity is ~ 0.4 kms^{-1} on ASDEX Upgrade and 0.8 kms^{-1} on MAST. However, this is not the true radial velocity of the ELM efflux because the poloidal and toroidal velocity components of the ELM filaments affect the measured time delay [5].

It is possible to construct a simple model for energy and particle losses during an ELM assuming that the filaments are linked to the core during a time τ_{ELM}. According to the predictions of non-linear ballooning mode theory, $\tau_{ELM} \sim (\tau_A^2 \tau_E)^{1/3}$ where τ_A is the Alfvén time and τ_E is the energy confinement time. During this time the filament acts as a conduit for losses from the pedestal region into the SOL either by convective parallel transport due to a reconnection process or by increasing the cross-field transport into the SOL. The total number of particles that could flow down *n* filaments is given by $N_{fil} = n\Gamma\sigma_{fil}\tau_{ELM}$, where Γ is the average particle flux density and σ_{fil} is the cross sectional area of the filament. The average particle flux density is calculated using the pedestal density and temperature respectively. The energy lost due to an ELM would then be $\Delta W_{ELM} = \frac{3}{2}k(T_i^{ped} + T_e^{ped})N_{fil}$. In linear ballooning theory the width of the filament perpendicular to the field line in the flux surface $\Delta_\perp \sim 2\pi a/nq$. On MAST and ASDEX Upgrade the minor radius (*a*), safety factor (*q*) and mode number (*n*) are similar and $\Delta_\perp \sim$ 9.4 cm, similar to the observed filament width. Assuming the filaments have a circular cross section i.e. $\sigma_{fil} = \pi(\Delta_\perp/2)^2$ then the ELM energy losses obtained from the model (assuming $T_i^{ped} = T_e^{ped}$) and measured in MAST and ASDEX Upgrade are given in Table 1. For an extrapolation to JET we have assumed that $\sigma_{fil} \propto a^2$. This assumption gives a reasonable agreement for both the lifetime and the energy loss of ELMs on JET. Before using this model to make predictions for future devices, such as ITER, it is important to test the predictions of τ_{ELM} and σ_{fil} on other existing machines.

Table 1 Predicted ELM energy losses based on parallel flow of energy along the filaments.

Machine	n_e^{ped} 10^{19} m^{-3}	T_e^{ped} eV	τ_{ELM} μs	σ_{fil} cm^2	ΔW_{ELM} (Model) kJ	ΔW_{ELM} (Exp) kJ
MAST	4	150	100	70	0.6	0.6
AUG	4	1000	200	70	24	26
JET	5	1000	330	280	196	300

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