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The temporal and spatial structure of ELMs in MAST

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The spatial distribution of energy released from the core plasma during Edge Localised Modes (ELMs) is a key area of study for ITER, where the resultant power loadings, both inside and outside the divertor region, have an important impact on the operating regime or possibly on the choice of plasma facing materials. In this paper, detailed measurements of the spatial and temporal structure of ELMs observed in the MAST [1] tokamak are presented, which confirm a number of predictions of the non-linear ballooning mode theory [2]. In particular, this theory predicts that a ballooning mode will evolve into a filamentary structure, which is highly elongated along the magnetic field lines. Even close to the linear marginal stability boundary the instability is predicted to grow explosively. Each filament narrows and twists to push between field lines on neighbouring flux surfaces on the outboard side while remaining unperturbed from its original location far along the field line. During this time, heat and particles are ejected from the confined plasma into the scrape-off layer and then travel along the field lines to the target plates.

The first evidence on MAST for the toroidal localisation and radial extent of the ELM outside of the plasma comes from a reciprocating Langmuir probe, which measures the ion flux at the outboard mid-plane in the scrape-off layer [3]. During a single ELM, 2 or 3 distinct periodic peaks in the ion flux are observed decreasing in amplitude. Each one lasts for ~5-10 μs and they are separated by 45-50 μs. The toroidal rotation velocity of the plasma edge is typically ~15 kms^{-1}. Interpreting the J_{SAT} peaks as filaments rotating with the plasma past the probe, gives a filament width of ~7.5-15 cm and a toroidal separation between filaments of ~75 cm. The toroidal circumference around the outside of the plasma is typically 9 m implying that the structure has a toroidal mode number in the region ~12. This is consistent with the most unstable modes typically predicted by the linear theory of ideal magneto-hydrodynamics[4].

Further evidence for the filamentary nature of the ELM and its temporal evolution comes from the high resolution ruby laser Thomson scattering system. Once per shot this system produces the electron density and temperature profiles across the mid-plane of the plasma. Figure 1a shows a typical outboard density profile obtained just before an ELM (t_{ELM} - 740 μs) the core density profile is very flat with a steep edge density gradient, dn_e/dr ~ 1.5x10^{21} m^{-4}. t_{ELM} is defined as the start of the ELM and, in this instance, is determined from the time at which the mid-plane D_α signal increases by 10 % of the value at the ELM peak.

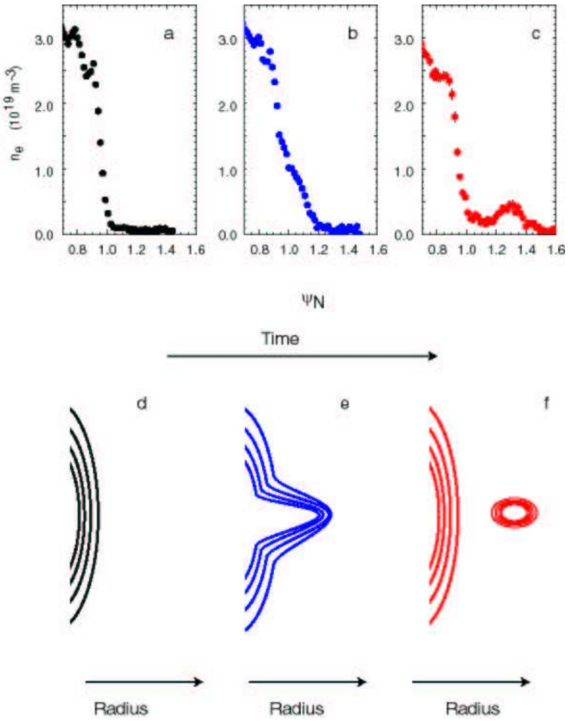

Figure 1 The time history of the effect of an ELM on the plasma.

Of the 40 discharges analysed so far, obtained during the rise time of the mid-plane D_α signal, 6 show the formation of a broad outboard tail in both the density (figure 1b obtained at (t_{ELM} + 140 μs)) and the temperature distribution and 4 exhibit a distinct structure in the density distribution in the scrape-off layer on the outboard side (at a radius of ~1.4 m in figure 1c obtained at (t_{ELM} + 180 μs)). This structure is also observed by a linear camera, detecting D_α light at different radial locations [5].

Since the Thomson scattering system makes measurements at a specific toroidal location and specific time, whether or not the filament is detected depends on its toroidal location at the time that the data is collected (the filament would rotate with the plasma). The reciprocating probe data implies a typical toroidal mode number of n=12 and a filament width of 15 cm. Taking an outer radius of the plasma of 900 cm, means that the

ELM toroidal coverage is ~ 180/900 ~ 20 % of the outboard surface at the mid-plane. This explains why the structure in the scrape-off layer is only observed by the Thomson scattering system 10 times in 40 discharges.

The following is a possible interpretation of the experimental observations. During the inter-ELM period steep gradients in both density and temperature develop just inside the separatrix in the pedestal region, reaching a peak shortly before the ELM (figure 1a shows a typical density profile). At this time the axisymmetric magnetic geometry is unperturbed (figure 1d). At the onset of the ELM, narrow plasma filaments develop, locally perturbing the outboard separatrix and flux surfaces in the scrape-off layer (figure 1e). Although these are extended along a field line, the perturbations appear to be poloidally localised at any particular toroidal angle. Thomson scattering measurements during this time, and for which the perturbation is in the field of view, show a flattening of the edge gradients. This is typically seen most clearly in the density profile, which forms a broad outboard tail (figure 1b). Disturbance to the outboard flux surfaces leads to enhanced cross-field transport of heat and particles into the scrape-off layer. Finally, by magnetic reconnection, the filament detaches from the core at the mid-plane (figure 1f), though possibly still remaining attached closer to the X-point region. Thomson scattering measurements with the correct spatial and temporal phasing now show a discrete, outboard density peak (figure 1c). Since the filament, at least in the early stages, is linked to the core the amount of energy in the plasma volume occupied by the filament is less than the amount of energy lost due to the ELM. During this time the filament acts as a conduit for losses from the pedestal region by distorting the outboard flux surfaces and increasing the cross-filed transport into the SOL. The amount of plasma energy in the volume occupied by the filament during the phases indicated in figure 1b,e and figure 1c,f can be calculated using $W_{filament} = \frac{3}{2} n_e (T_e + T_i) V_{filament}$, where $V_{filament}$ is the volume of the filament and assuming $T_i = T_e$. The estimated energy contained in each filament is 4 J (figure 1b) and 1.2 J (figure 1c) given by the measured density profile perturbation. Even assuming that there could be 10-15 filaments, the total energy content (< 60J) is only a small fraction of the energy loss due to this ELM of ~ 500 J. Hence this shows that the filament is not a blob of plasma that is breaking away from the core but is a finger that connects back to the core, providing a path for the heat to escape from the core to the scrape-off layer.

All the data we have described so far can only provide a one-dimensional view around the plasma mid-plane. To confirm the filamentary structure requires a two-dimensional measurement. This final evidence comes from a unique capability on MAST to view a large fraction of the plasma surface and hence obtain a photograph of an ELM using a high-speed camera with a short (25 μs) exposure time. Provided the plasma rotation is sufficiently slow so that the features are not blurred, clear filaments are observed (figure 2).

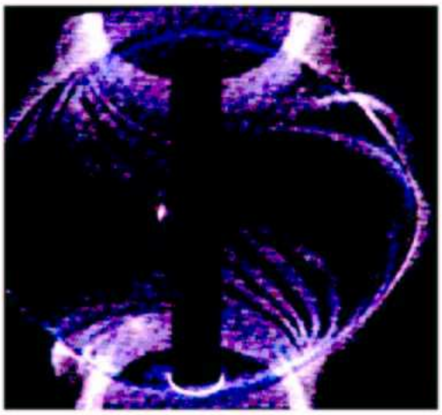

Figure 2 High-speed video image of the MAST plasma obtained at the start of an ELM, showing evidence for a filamentary structure.

Taken together, the observations presented in this paper provide strong evidence for the ELM having a filament like structure, which is generated on a 100 μs timescale, erupts from the outboard side while remaining connected to the core plasma. Such a structure would be expected from the theory of the non-linear evolution of ballooning modes, adding support to the idea that peeling-ballooning modes are responsible for triggering ELM events.

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