29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, O-3.24 (2002)

The Fine Structure of ELMs

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Since the discovery of the H-mode in the ASDEX tokamak, many investigations of the phenomenon called ELMs (edge-localised modes) have been made. ELMs are an instability associated with a rapid loss of particles and energy from the edge plasma. It is known that a temporal resolution in the μs range is necessary to resolve the fast changes during an ELM. However, hardly any investigation exists of the *spatial* fine structure of ELMs. We present here measurements with Langmuir probes and with a dedicated H_α fluctuation diagnostic in the edge and scrape-off layer (SOL) of the JET and "old" ASDEX tokamaks. It is our aim to demonstrate that ELMs display a fine structure with very strong peaks in the fluctuating signals on the scale of $\sim 1\,\mathrm{cm} \perp \boldsymbol{B}$, and of 10–50 μs duration. The signals from the main plasma edge are compared with signals from the divertor. In addition, estimates of the radial transport due to fluctuating E×B fluxes during ELMs are given for the case of JET.

1 Spatial fine structure of ELMs in H_α light in ASDEX

In the midplane of ASDEX, an H_α fluctuation diagnostic (HFD) was used, which allowed to record the H_α/D_α radiation from the plasma edge with photomultipliers at 16 poloidal positions, spaced in steps of 6 mm [1]. A constant neutral density is provided by gas puffing.

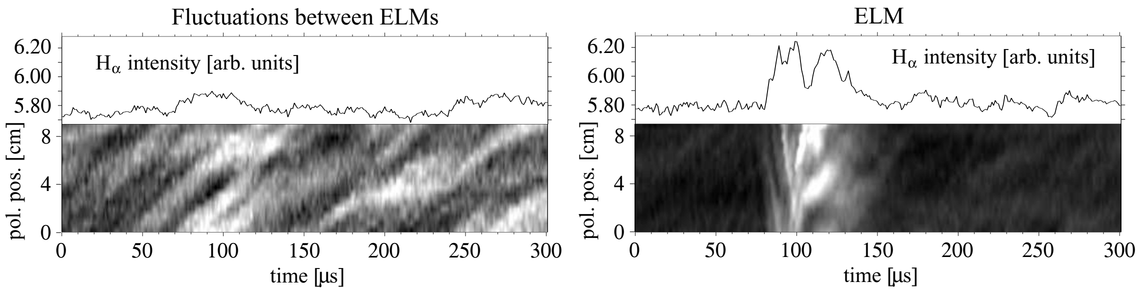

Figure 1: Grey scale image of the 16 poloidally displaced channels of the H_α fluctuation diagnostic at ASDEX for a time interval in between ELMs and during an ELM, showing the "normal" fluctuations and their typical poloidal size, lifetime and poloidal propagation and the substructures during the ELM on a time scale of 20 μs (bottom). The upwards direction is the ion diamagnetic drift direction. The corresponding time traces from one channel are depicted in the top panels.

In fig. 1, the spatio-temporal properties of the "normal" density fluctuations in the SOL of ASDEX are compared with those during ELMs. In between ELMs, the poloidal velocity of the structures is rather constant for stationary conditions — in our example

$(1100 \pm 300)\,\mathrm{m/s}$. In contrast, each ELM displays a different spatio-temporal structure. The spatial scale of the substructures seems to be comparable to that of "normal" fluctuations. However, the poloidal velocity of the substructures is in general much higher during ELMs and exhibits a much larger scatter; often even structures with opposite poloidal velocity occur during one ELM. In our example, poloidal velocities between $-6500\,\mathrm{m/s}$ and $+7000\,\mathrm{m/s}$ are found ("+" denoting the ion diamagnetic drift direction). Only a lower bound of 10–20 μs for the lifetime of these substructures can be given.

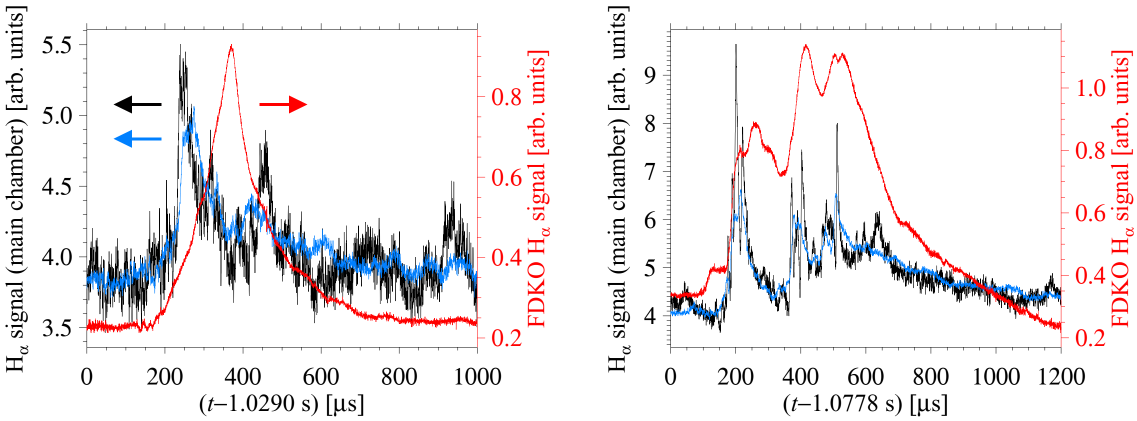

Figure 2: Comparison between signals of the H_α fluctuation diagnostic in the midplane of ASDEX (black: single channel; blue: average over 8 channels, corresponding to a poloidal region of 9 cm) and the "FDKO" H_α monitor (red) for two different ELMs.

For comparison, we display in fig. 2 two ELMs recorded by the HFD together with the "FDKO" signal, an H_α monitor signal from a photodiode observing the upper outer divertor plate with low spatial resolution. An averaging over 8 channels of the HFD, corresponding to a poloidal average over 9 cm, does hardly reduce the strong peaks and carries still much more similarity to the signal of one single channel than to the FDKO signal. One reason for this difference may be that in the divertor, the neutral gas is exclusively due to recycling. During an ELM, the plasma flux onto the target plates increases strongly, whereas the neutral gas density in the observation region of the HFD is dominated by the constant gas puffing.

2 Langmuir probe measurements of ELMs and related E×B transport in JET

In the JET tokamak, a reciprocating Langmuir probe (RLP) system at the top of the plasma and several of the Langmuir probes integrated into the divertor target plates of the Mark IIA divertor were used for ELM investigations. The RLP system was fitted with a head comprising six carbon tips, arranged in two triples with poloidal spacing, measuring floating potential (Φ_{fl}) fluctuations with the two outer tips and ion saturation current (I_{sat}) fluctuations with the central tip. The three tips of each triple were placed on the same flux surface, and the centres of the triples were separated by 1.3 cm in radial and 2.3 cm in poloidal direction [2].

The measurements of these probes for one ELM are displayed in fig. 3. Like in the HFD signals from the main chamber of ASDEX, strong peaks in I_{sat} occur with a duration of 10–50 μs. Most strong peaks can be identified in both I_{sat} signals, however, their amplitude and the time lag between the two tips varies: It is not always the tip closer to the separatrix which detects the higher amplitude or on which a peak occurs first. This indicates a spatial structure $\perp$ $\boldsymbol{B}$ on a scale smaller than the probe tip separation of 2.7 cm.

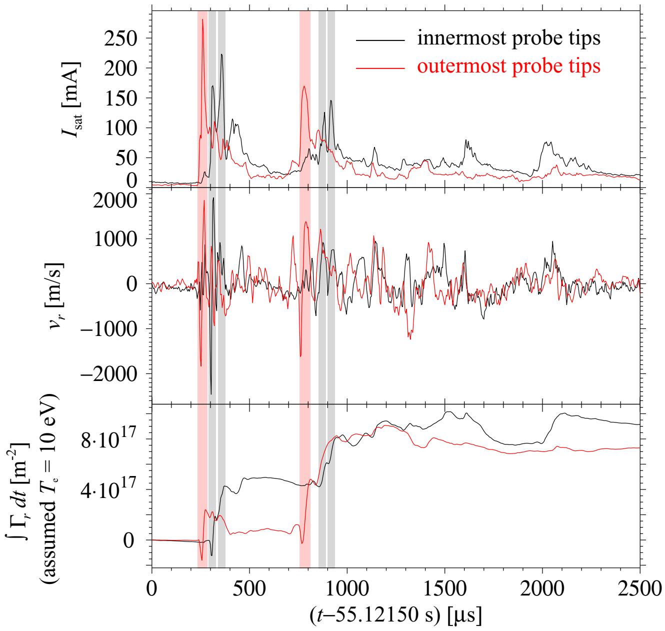

Figure 3: Measurements of the two Langmuir probe tip triples on the RLP system during one ELM in a JET 12 MW NBI discharge. The vertical grey and rose bars are intended to help relating the behaviour of the different quantities for the strongest radial transport events.

On a "slow" time scale (above 1 ms) the signals from main plasma and divertor Langmuir probes are very similar. On top of this "slow" time scale, peaks of 10–50 μs are also present on several divertor probes, but in most cases their amplitude relative to the signal amplitude between ELMs is much smaller than for the RLP tips.

The arrangement of the probe tip triples on the RLP system measuring Φ_{fl} and I_{sat} fluctuations allows to calculate the fluctuation-induced radial transport due to fluctuating radial E×B drifts, if one neglects the existence of temperature fluctuations. As this neglect may appear to be a very bold assumption in the case of ELMs, we shall interpret the results of our analysis only as a rough estimate of the true radial E×B transport during an ELM.

In the two lower panels of fig. 3, the fluctuating radial E×B velocity $\tilde{v}_r$ and the time integral of the fluctuating radial particle flux $\tilde{\Gamma}_r$ are depicted (assuming an average temperature of 10 eV). The latter trace demonstrates that the net radial flux is indeed directed outwards, and the distinct steps show that the dominating contributions to this transport happen during those very brief intervals of 10–50 μs, which are marked by the peaks in the I_{sat} signals. The radial E×B velocity during these intervals can reach 1000–2000 m/s. Since we cannot follow individual peaks longer than they are registered on a single probe tip, the duration of 10–50 μs is a lower estimate of their lifetime, and together with the radial velocity we obtain a lower estimate of 1–10 cm for the radial movement of plasma within these structures.

3 Discussion

The use of diagnostics with a resolution of a few millimetres $\perp$ $\boldsymbol{B}$ has revealed that ELMs indeed display substructures on this scale in the SOL of tokamaks. This fine structure could either be inherent to the instability underlying an ELM, or it could be generated as a secondary effect once plasma from the confinement region is injected into the SOL. This plasma of much higher density and temperature than is usual for this region could well generate turbulent structures with properties not normally found in the SOL. In order to decide this issue, diagnostics with comparably good spatial resolution would be required for the steep gradient region inside the LCMS, where ELMs are believed to originate.

The strong peaks in density (and presumably also in temperature) remind of the blobs of high-pressure plasma in a low-pressure background, which were suggested to explain the flat gradients in the outer SOL [3].

The peaks are associated with high radial velocities, which may be an explanation why their amplitudes are higher in the main chamber signals than in the divertor signals: Those substructures causing the strongest peaks in the SOL of the main plasma may propagate sufficiently fast in radial direction, such that they hit the baffle plates before a significant amount of hot high-density plasma can get into the divertor along the magnetic field. This would be compatible with the width of the divertor throat of a few centimetres and the radial E×B velocities of 1000–2000 m/s estimated from the JET RLP data.

In [3], the authors suggest that those blobs propagate in radial direction due to the same mechanism as discussed for a SOL instability in [4, 1]. In this model, the amplitude of the potential perturbation associated with a blob, and hence the radial E×B velocity, is determined by the sheath boundary conditions at the target plates. In a background plasma of $5 \cdot 10^{19}\,\mathrm{m}^{-3}$ and 20 eV, $B = 2.5\,\mathrm{T}$, curvature radius of B of 2 m and correlation length of 20 m of the blob along the magnetic field, a blob of 3 cm size, $2 \cdot 10^{19}\,\mathrm{m}^{-3}$ density and 200 eV would then indeed drift radially with $\sim 1000\,\mathrm{m/s}$.

4 Conclusions

The use of fluctuation diagnostics with high spatial and temporal resolution has revealed a fine structure in ELMs which was so far unknown.

Consequently, the heat loads to the target plates of fusion devices, and possibly to sections of the wall and in-vessel diagnostics, are concentrated during ELMs on scales of a few centimetres and 10–50 μs rather than averaged over the whole power-carrying layer and over the total duration of the ELM.

The target plate instability model discussed earlier, applied to high-density and high-temperature blobs in the SOL with the experimentally observed scale lengths, yields a fair agreement with the behaviour found for the substructures of ELMs.

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