*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, O-4.031 (2008)*

Observations of ELM pre-cursor structures using Beam Emission Spectroscopy in MAST

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The origin of Edge Localised Modes (ELMs), especially the large type I variety has been the subject of intense study since their discovery. According to the peeling-ballooning mode theory these instabilities are triggered when the combined effect of the pedestal pressure gradient and the edge current density makes an edge localised ideal MHD mode unstable. Although this mode is expected to grow on a fast timescale several experiments revealed the presence of slowly growing or saturated precursors before this ELM type. A recent study of type I ELMs on MAST [1], using line integrated density measurements, pointed to the existence of a precursor with about 10 kHz frequency without the capability of localising the mode. A recently installed trial Beam Emission Spectroscopy (BES) diagnostic[2] has a high-frequency local density measurement capability therefore an attempt was made to study the location and temporal structure of these precursors and their relation to ELMs.

The measurements presented in this paper were made in a strongly off-axis 1.5 MW NBI heated lower single null divertor configuration with I_p=600 kA, $q_{95}\approx 3$. In the L-mode phase these discharges exhibited sawteeth. In H-mode phase large ELMs appear, the appearance of which seems to be related to MHD events in the core plasma.

Diagnostics

The present BES diagnostic uses an existing CXRS optics observing the heating Deuterium beam in a direction approximately aligned to the magnetic field lines. The Doppler shifted D_α light is filtered by a single interference filter and imaged onto 8 avalanche photodiodes. The signals are amplified with 1 MHz bandwidth and sampled at 2 MHz, the resulting Signal to Noise ratio is 5-10. The 8 channels have about 4 cm radial separation in the plasma and they cover the range from the SOL to about $r/a\approx 0.5$. The radial resolution of typically 3-4 cm is defined by the misalignment of the lines of sight and the local magnetic field across the heating beam width. At the edge these signals are proportional to the local plasma density, while deeper in the plasma they drop to half amplitude over a length of 20-30 cm due to beam attenuation. The signals are somewhat contaminated by radiation from a Carbon line from the plasma edge which could not be separated by the single interference filter.

Besides the BES other diagnostics were also used in this study: a 30-channel horizontally viewing and a 16 channel tangential soft X-ray array with 12 μm Be filter foil, single-channel D_α detectors looking into the divertor region, the inner wall and tangentially at the plasma edge, an array of Mirnov coils and a 100 kHz frame rate fast camera looking at a fraction of the poloidal cross-section at the outer top of the plasma.

Three phases of the events preceding an ELM have been identified: precursor oscillations developing finger-like structures across the separatrix, wall interaction of the fingers and finally the ELM phase.

Precursors at the pedestal

Fig. 1. shows typical BES signals and BES light profiles at selected times before an ELM together with the magnetic configuration of the same MAST discharge. The signals were numerically integrated for 2 μs which results in about 5 mV electronic noise level. Several ms before the ELM sinusoidal oscillations appear at the pedestal with 12 kHz frequency. About 2 periods before the ELM this modulation develops into positive peaks in the BES signals

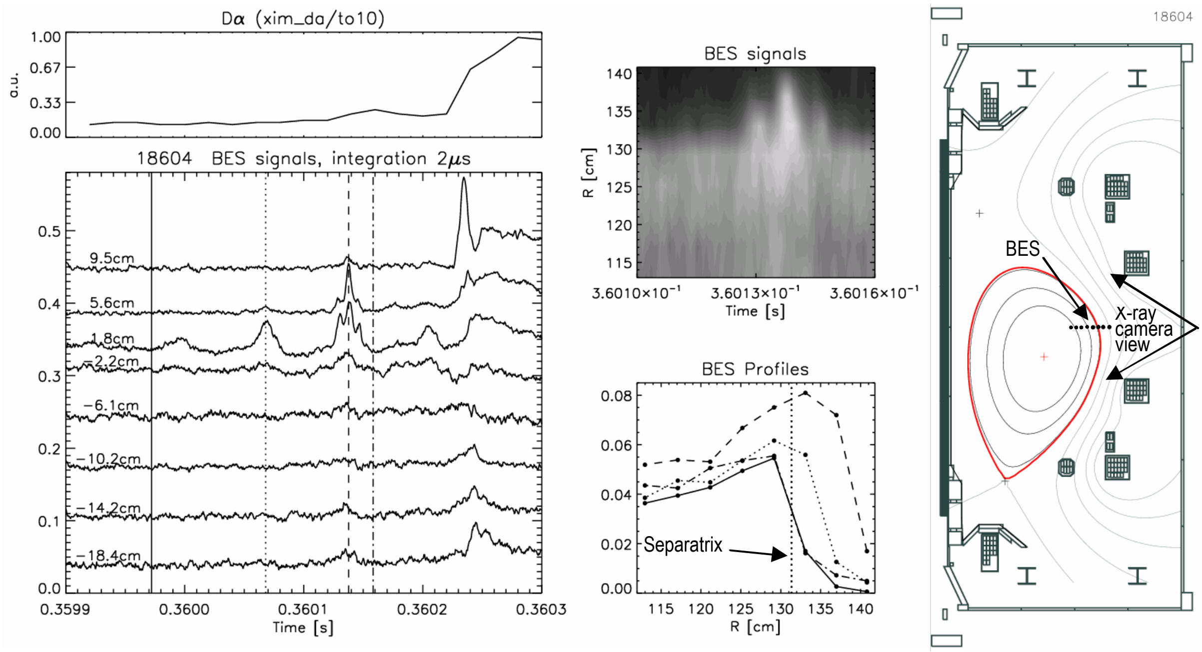

Fig. 1. BES signals (left, shifted vertically by 0.06 units) and divertor D_α before an ELM . The numbers above the BES traces show measurement positions relative to the separatrix, positive numbers are outside. The vertical lines indicate times for the BES profiles. The magnetic configuration is shown to the right. The contour plot shows the BES signals during the last pulse.

measuring in the outer part of the pedestal. The profiles clearly show that these correspond to a quick outward shift of the pedestal by up to 8-10 cm. The profiles also show a general increase but this might be caused by edge CII line radiation. It has to be realised that the movement of the profile is not sinusoidal as in that case negative spikes would have to be observed inside the separatrix as well. As the plasma flows toroidally the appearance of the pulses should correspond to the passing of protrusions (fingers) of the pedestal. At t=0.36014s this finger splits up into three smaller structures (see the grayscale plot) of which the middle one protrudes deeper into the SOL. This splitting could be observed only in two cases out of about 20 events, the second case developed two sub-structures. In other cases an asymmetric narrowing of the pulses is often observed. It has to be noted that the separatrix position is determined from D_α profile constrained EFIT equilibrium calculations and is expected to have a few cm uncertainty.

The finger-like precursors are not always seen before ELMs. Sometimes sinusoidal oscillations are observed at the same frequency which also continue after the ELM and sometimes no oscillations are seen at all. These modes can also be seen during the whole H-mode phase of the discharge in Mirnov coil signals, the X-ray camera and sometimes with lower amplitude in pedestal BES channels as well. Except for a few periods before the ELM the BES signals appear to be sinusoidal. The toroidal mode number from magnetic signals appeared to be dominantly n=1 with some washboard-type harmonics. The poloidal mode structure could be studied by analysing phase jumps in the X-ray camera. Far from the ELMs a core m=1 mode is seen. Before an ELM the mode extends to the edge and the phase structure becomes more complex: 3-4 phase jumps are resolved.

Wall interaction of fingers

At the time when the fingers protrude to the bottom of the pedestal (5-10 cm outside the calculated separatrix position) the D_α line radiation increases somewhat showing an increased interaction with plasma facing materials, e.g. divertor targets or other in-vessel structures. The increased visible emission is also observed in fast camera (100 kHz frame rate) images as a strongly radiating layer appearing for 10-20 μs around the separatrix. The camera observes only a small fraction of the poloidal circumference therefore the poloidal extent of this layer cannot be determined.

The time evolution of the vertical distribution of the line integrated soft X-ray intensity is shown in *Fig. 2.* together with some other signals in a case when an ELM is not triggered by this mode. At the time when the narrow fingers appear in the pedestal the X-ray signals show the apparent poloidal motion of a few narrow structures. In the tangential X-ray camera these filaments appear only on the outboard edge and move toroidally in the co-current direction, that is they follow the plasma toroidal flow velocity. Immediately following the appearance of these filaments the X-ray radiation strongly increases in a belt at the plasma edge. The increase occurs on a timescale of 100μs by up to 100% and stays at this elevated level until the next ELM. In *Fig. 2.* this happens after 1 ms, but in most of the cases an ELM occurs after 100-150 μs. Without an ELM the edge X-ray signal stays at an elevated level for even 10-20 ms. Regardless of the time delay the X-ray signal drops during the ELM. In *Fig. 2.* strong mode activity is seen in the X-ray signals, but this is not always the case.

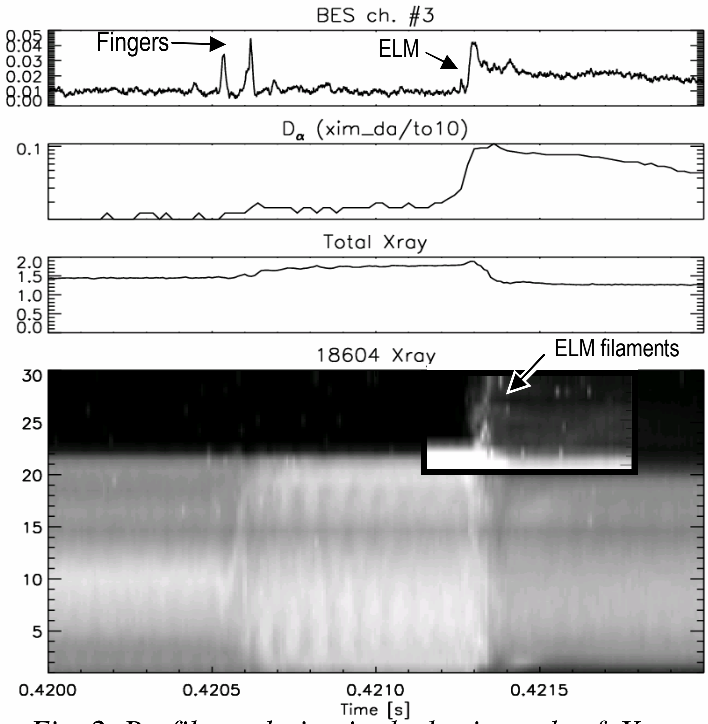

Fig. 2. Profile evolution in the horizontal soft X-ray camera (bottom), the total X-ray intensity, the divertor D_α and the BES signal at the middle of the pedestal. The greyscale intensity is magnified by 3 in the upper right corner of the bottom figure.

The increase of the X-ray signal at the edge can arise from a change of density, temperature or Z_{eff}. Neither Thomson scattering nor BES show a substantial change which could explain a factor of 2 increase in the X-ray intensity, therefore the explanation should be a substantial increase of the impurity content at the plasma edge.

After this wall interaction event the fingers retract as seen in both *Figs. 1. and 2*. If an early (<1 ms) ELM occurs the filaments are not seen again before the ELM. If the next precursor event occurs some 10 ms later the fingers appear again and the X-ray radiation increases from this already elevated level. This behaviour is consistent with the idea that each wall interaction event ejects an impurity cloud into the plasma edge.

Transition to ELM

At the ELM X-ray signals clearly show the ejection of multiple hot filaments into the SOL as it is seen by the X-ray camera in *Fig. 2.* These filaments never appear during the wall interaction event. The appearance of filaments is also seen in fast camera measurements as was published elsewhere[1]. The density profile evolution cannot be reliably followed by the current BES diagnostic as the signals are contaminated by strong variations of edge CII radiation, therefore the ELM phase is not studied in any more detail in this paper.

Discussion

From the observations presented in the paper the following sequence of events can be deduced. An m/n=1/1 mode is sometimes present in the MAST core plasma during H-mode. According to linear simulations with the MISHKA code it is identified as an internal kink mode destabilised by the pressure and flat q profile. The mode amplitude nonlinearly saturates and as discharge conditions evolve on the energy confinement timescale it slowly extends towards the edge. There its poloidal mode number adjusts to the local q value, therefore at the edge m≈3-4. The mode modulates the pedestal pressure profile and at the steepest part the growth rate is increased locally. This leads to a nonlinear growth of primary fingers (broad field-aligned ribs on the LFS) into the SOL on a 100μs timescale which tend to undergo further disintegration into smaller parallel filaments on an order of magnitude shorter timescale. The plasma fingers protrude 5-8 cm outside the pedestal and finally get into contact with some material structure. The subsequent cooling removes the local pressure drive and the fingers retract. The material contact releases a cloud of impurities substantially increasing Z_{eff} in the plasma edge.

The relation of ELMs to the above finger-wall contact is a further question of interest. The fact that not all ELMs in the studied discharges are preceded by fingers in the BES diagnostic might indicate that their wall interaction is just one ELM triggering possibility besides naturally occurring ELMs. The wall contact of the fingers can deplete plasma energy from a flux tube very similarly to an injected pellet, therefore similar ELM triggering mechanisms might be in action in both cases[3]. From the available limited number of SND measurements on MAST it is difficult to conclude whether the observed mechanism is a peculiarity of this configuration or has some wider significance. However, an example has been found in TCV in similar lower SNL discharges with periodically occurring large ELMs. In this case the ELMs are always preceded by a series of pulses on signals of an AXUV bolometer camera line of sight looking vertically along the LFS plasma edge. Similarly to MAST in this case the pulses are also phase locked to a global mode.

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