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Study of the ELM fluctuation characteristics during the mitigation of type-I ELMs

A V Bogomolov¹, I G J Classen¹, J E Boom², A J H Donné^{1,3}, E Wolfrum²,
R Fischer², E Viezzer², P Schneider², P Manz², W Suttrop², N C Luhmann Jr.⁴
and the ASDEX Upgrade Team

¹*FOM-Institute DIFFER, Dutch Institute for Fundamental Energy Research,
3430 BE Nieuwegein, The Netherlands*

²*Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, 85748 Garching,
Germany*

³*Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*

⁴*University of California at Davis, Davis, CA 95616, USA*

E-mail: A.Bogomolov@diffr.nl

Abstract

The transitions from type-I to small edge localized modes (ELMs) and back are studied by the electron cyclotron emission imaging (ECEI) diagnostic on ASDEX Upgrade (AUG). ECEI measurements show that the average poloidal velocity of temperature fluctuations of both type-I ELM onsets and small ELMs is the same and is close to 5-6 km/s. Radially, the temperature fluctuations are distributed in the same narrow region of 2 cm in between $0.975 \leq \rho_{\text{pol}} \leq 1.025$ with associated poloidal mode numbers $m = 96 \pm 18$ and toroidal mode numbers $n = 16 \pm 4$. The observed fluctuations related to both type-I ELMs and small ELMs vary over the transition simultaneously, however, showing slightly different behaviour. The similarities between type-I ELMs and small ELMs observed on AUG suggest that they both have the same nature and evolve together. In the transition phase a temperature fluctuation mode ('inter-ELM mode') appears, which becomes continuous in the mitigated ELM phase and might cause the ELM mitigation. The mode characteristics (velocities, frequencies and wave-numbers) obtained in the analysis can be further used for the direct comparison in various code simulations.

(Some figures in this article are in colour only in the electronic version)

1 Introduction

In the high confinement mode (H-mode) of a tokamak plasma, a magnetohydrodynamic (MHD) instability called the edge localized mode (ELM) appears. These modes expel plasma particles and energy resulting in high power loads on the divertor and, in case of reactor operation can cause intolerable erosion of the first wall materials. Therefore, study of ELMs is needed in order to be able to better control these events in future devices [1].

The good confinement is usually accompanied by so called Type-I ELMs. They cause fast losses of a significant fraction of the stored energy in a period of time in the order of several hundred microseconds [1]. A large part of this energy goes to the divertor plates which can have adverse effects on the divertor material. In general, type-I ELMs do not reduce the lifetime of the divertor in current devices, but they will lead to unacceptable damage of the divertor in future devices, such as ITER [2].

Also several other types of small ELMs exist, with different properties (characterized by amplitude, repetition rate, etc.), like type-II ELMs, type-III ELMs or grassy ELMs and even regimes without ELMs, such as in the quiescent H-mode (QH-mode) [1][3]. Unlike the type-I ELMs, the small ELM regimes are associated with smaller energy losses and, as a consequence, a reduced peak heat flux to the divertor plates [4].

It is still not clear whether type-II ELMs on AUG are similar to the grassy ELMs on JET [4].

One of the ways to deal with type-I ELMs is modification of the plasma flux surfaces by means of application of 3D magnetic perturbations. There are two successful scenarios possible: ELMs can either totally disappear ('ELM suppression'), as it has been shown on DIII-D [5], or ELMs can become smaller with simultaneous increase in their frequency ('ELM mitigation') [6].

At ASDEX Upgrade it is commonly observed that above a certain threshold in density, a transition from the large type-I ELMs to much smaller ELM crashes occurs. The application of active in-vessel off-midplane saddle coils ('B-coils') [7] leads to an increase of density which cause the type-I ELMs to disappear [8] while smaller and more frequent crash events start to dominate [9]. In contrast to type-I ELMs, in the small ELM regime there is an almost continuous succession of small crashes. This fact is also reflected in the thermal current in the outer divertor plates resulting in a "grassy"-like signal.

Experiments on ELM control with magnetic perturbations were also performed on JET. Four coils, so-called Error Field Correction Coils (EFCC),

unlike B-coils of ASDEX, are located outside JET vacuum vessel and can produce $n = 1$ or $n = 2$ perturbations. In the experiments an ELM mitigation was achieved [10].

The understanding of ELM control mechanism is essential for designing the future devices. Though there is no complete theory, one of the explanations for the mechanism which leads to ELM mitigation with the use of magnetic perturbations is the stochastization of the magnetic field at the plasma edge [11].

In this paper the scenario with application of B-coils will be used (described in more detail in the next section) to study the temperature fluctuations associated with ELMs during the transition from type-I to mitigated ('small') ELMs. As here we are mostly interested in how type-I ELMs are substituted by small ELMs during the transition, and also as there are large similarities in both type-II and type-III ELMs, the exact type of achieved small ELM regime will not be discussed.

There are two main objectives in this article. The first one is, using the capabilities of the ECEI diagnostic, to show new details on how ELM crashes occur, meanwhile providing a comparison between type-I ELMs and small ELMs. The second objective is, using the obtained details, to try to answer the question, whether the type-I ELMs change their behaviour during the transition, causing them to disappear, or whether the small ELMs become dominant and prevent type-I ELMs from developing.

The paper is organized as follows: in section 2 the details of the experiment are given, introducing the shot parameters and the scenario for the transition from type-I ELMs to small ELMs. Section 3 is dedicated to studying the characteristics of type-I ELMs and small ELMs during the transition. First of all, the type-I ELM cycle is explained, kinetic profiles related to different types of ELMs are introduced, then the mode intensity of both modes is considered, followed by the data processed on a basis of conditional averaging. The following subsections show a comparison of mode localization, and then, based on a 2D Fast Fourier Transform (2D FFT), average mode velocities are calculated. A discussion is given in Section 4.

2 Experimental set-up

To study the transition from the type-I to the small ELM regime the discharge #26080 has been analysed. An overview of the discharge is presented in Fig. 1. The shot has the following parameters: $B_t = -2.5$ T, $I_p = 0.8$ MA, $P_{\text{NBI}} = 7.3$ MW and $P_{\text{ECRH}} = 0.9$ MW. In the shot the off-midplane mag-

netic perturbation coils (B-coils) are applied between $2.0\text{ s} \leq t \leq 5.3\text{ s}$. Four upper toroidal rings (out of eight) and four lower ones were used with 90° phase shift (odd parity), creating the perturbation with the toroidal mode number $n = 2$. The safety factor $q_{95} = 5.7$. The transition to the small ELM regime starts, when the density at the pedestal top reaches $6 \cdot 10^{19}\text{ m}^{-3}$. When the B-coils are turned on, the edge density increases, which triggers the transition. During the transition phase smaller crashes start to appear in between the type-I ELM crashes, while the type-I ELMs appear less frequently until they totally disappear. At this moment the edge density reaches $6.7 \cdot 10^{19}\text{ m}^{-3}$. As the gas puff is reduced and the density falls back to $6 \cdot 10^{19}\text{ m}^{-3}$, the type-I ELMs appear again.

Different phases of the shot are marked in Fig. 1, which shows the change in the number of type-I ELMs and small ELMs during the transition, as well as changes in the divertor thermal current. Divertor thermal current is a signal based on the current which is produced by thermocouples in the divertor when the divertor plates are exposed to thermal loads. Here the divertor current is used to calculate the amount of ELMs and is also used to automatically distinguish between type-I ELMs and small ELMs by defining corresponding thresholds. Each point in Fig. 1d represents the number of ELMs which occurs in a time window of 100 ms. The shot can be divided into four different phases: I) type-I ELMs with an amount of small ELMs in between; II) the transition phase from type-I to smaller ELMs: the amount of type-I ELMs gradually decreases, while small ELMs increase in their number; III) the phase of mitigated type-I ELMs, where only small ELMs are observed; IV) the back transition phase, where type-I ELMs appear again, while the amount of small ELMs decreases. In this paper the type-I ELMs were analysed in the 1st ("before the transition"), 2nd ("during the transition") and 4th ("back transition") phases, while small ELMs were analysed in the 2nd, 3rd and 4th phases, where they mostly appear. Note that some small ELMs are already observed before the transition starts.

In this paper the electron temperature fluctuations associated with both type-I and small ELMs have been investigated using the Electron Cyclotron Emission Imaging (ECEI) diagnostic on AUG [12]. The ECEI system at AUG is a 2D diagnostic which consists of a linear array of 16 detectors, each of which acts as a standard (1D) ECE radiometer, looking at different vertical position in plasma. Each 1D radiometer has 8 radial channels, which results in totally 128 channels for the ECEI system and covers an observational area of $\sim 10 \times 40\text{ cm}$. The size of the spot determining the spatial resolution

Figure 1: Different shot phases. The gray region (I) is a typical type-I ELMs regime. The blue region (II) is the transition to small ELMs regime. The green region (III) indicates mitigated ELMs (small ELMs) regime. The red region (IV) is the back transition to type-I ELMs. Type-I ELM crashes are marked with black dots, while small ELMs are represented by red stars. a) Heating power (NBI in red and ECRH in black) b) Divertor thermal current (black) and B-coils current (red). c) Line integrated plasma density at the pedestal top (black) and D_2 gas puff (red). d) ELM frequency behaviour. Shown is the number of ELMs (type-I and small) per 100 ms as a function of time.

of the diagnostic is 2.5 cm in vertical and 1.5 cm in radial direction. For the work presented in this paper, the ECEI observational area of ECEI is positioned at the low field side (LFS), centered vertically on the mid-plane and radially covering a region on either side of the separatrix. The sampling rate of 200 kHz is chosen. This allows the observation of variations in the 2D electron temperature evolution during the ELM cycle in detail [13].

In order to have reliable electron temperature measurements the optical thickness of the plasma should be high enough for the corresponding wavelengths. This condition is satisfied in the plasma region deep inside of the separatrix, but is starting to be violated at ~ 1 cm inside the separatrix. When close to the separatrix the temperature measurements become affected by the density and, therefore, one can not refer to the ECEI measurements as pure electron temperature anymore. However, for the current research this is not an important issue, as there are other characteristics of the plasma fluctuations studied rather than the absolute temperature values. For instance, mode velocity is not affected by misinterpretation of the absolute temperature

values, as there only relative changes in temperature are needed. Another issue of the ECEI measurements is emission profile broadening. The most significant broadening mechanisms for cyclotron radiation are relativistic and Doppler broadening [14], which for the ECEI are of the same order of magnitude and are resulting in the radial resolution of 1.5 cm for the diagnostic in the optically thick regime.

3 Investigation of ELM characteristics

3.1 ELM cycle

In Fig. 2a one type-I ELM and three small ELMs are presented as seen by the divertor thermal current. The type-I ELMs and small ELMs can be easily experimentally distinguished by means of the divertor current: the signal corresponding to type-I ELMs has much higher amplitude and the duration, than the signal corresponding to small ELMs. Considering a type-I ELM cycle, it can be divided into two phases: the type-I ELM crash phase and the recovery phase. The type-I ELM crash itself also can be divided in two phases. The first phase consists of an ELM onset mode [13] (three frames of ELM onset development are shown in Fig. 2b), where relatively coherent, but short lived temperature fluctuations are seen and which are one of the objects of study in this paper. In Fig. 2c the coherent temperature oscillations are seen as inclined bright lines. The second phase is the crash itself, where temperature fluctuations become chaotic and result to a drop of plasma temperature. During the temperature drop, hot structures with a poloidal extent of several centimeters (so-called 'filaments') are expelled out of the plasma [13].

After the temperature has reached its minimum, it starts to increase again in the recovery phase. During this phase some coherent plasma oscillations can occur ('inter-ELM modes') [13], and also small ELMs (Fig. 2a in green) occur in this phase.

Unlike type-I ELMs, small ELMs do not have the crash phase with chaotic temperature fluctuations and filaments. Instead only the coherent temperature fluctuations phase exist, which is similar to the type-I ELMs onset phase (Fig. 2d). This similarity suggests to compare the properties of the small ELMs with only the onset phase of the type-I ELMs.

The comparison of the properties of small ELMs to type-I ELM onsets is one of the main points of interest in this paper. Related to this, some properties of 'inter-ELM' modes will also be investigated, the description of

Figure 2: Shot #26080. a) Thermal divertor current. The type-I ELM is marked with the red band, while small ELMs are marked with green ones. b) ECEI data during the type-I ELM crash: a fluctuation rotating in the electron diamagnetic direction (in the laboratory frame) is observed. c) One vertical chord of the ECEI is plotted as a function of time. Thin black lines indicate the three moments of time used in 'b', and mark the beginning of the ELM onset. d) One vertical chord of ECEI is plotted as a function of time, corresponding to a type-I ELM (left) and a small ELM (right). e) Spectrogram built on the basis of plot 'd' . f) Integrated spectral amplitudes, obtained from plot 'e' by integration over frequencies in the range of 12 – 70 kHz.

an 'inter-ELM' mode will be given in subsection 3.8.

3.2 Plasma kinetic profiles

In order to compare the conditions which trigger type-I ELMs and small ELMs, plasma temperature and density profiles are considered prior to the crash events. The density profile is delivered by integrated data analysis (IDA) [15], whereas electron temperature profile is built on 1D ECE data. According to the 'two point model' [16] the electron temperature at the separatrix at AUG should not exceed 100 eV. To satisfy the model the ECE profiles were shifted in such a way that the averaged profile at the separatrix $T_e^{\text{sep}} = 100$ eV. For Fig. 3 the time window, where the events are considered, is taken during the transition phase (2.3 – 3.5 s.) in order to make the direct comparison of the profiles before a certain type of ELM is triggered. Each profile is taken ~ 1 ms prior to the actual crash, which provides that the data is unaffected by the following crash.

Figure 3: Plasma profiles in the transition phase to small ELMs regime. Density (IDA) and electron temperature (ECE) are taken at the moments prior to type-I ELMs (red crosses) and prior to small ELMs (blue circles). Solid lines indicate averaged profiles.

As it is seen from Fig. 3, the kinetic profiles, which cause the triggering of type-I ELMs, are very similar to the profiles, triggering small ELMs. The scatter in the density profiles is large, which does not allow to conclude any differences in the profiles. Temperature data has less scatter, however, no difference in the averaged profiles is also observed.

Fig. 4 compares the profiles preceding ELM triggering for type-I ELMs and small ELMs, also in different phases. The type-I ELMs preceding profiles

Figure 4: Plasma profiles for type-I ELMs before the transition to the small ELMs regime and for small ELMs after the transition. Density (IDA) and electron temperature (ECE) are taken at the moments prior to type-I ELMs (red crosses) and prior to small ELMs (blue circles). Solid lines indicate averaged profiles.

are taken in the pure type-I ELM phase, while small ELM preceding profiles are corresponding to the pure small ELM phase. Again, the large scatter in the density data does not allow to conclude on the differences in the density gradients in the pedestal region. The higher density at the pedestal top, which is situated according to the IDA density profile at $\rho_{\text{pol}} \sim 0.95 - 0.97$, is caused by application of the B-coils, which led the plasma into the small ELMs regime. As for the temperature, the averaged profiles are also very similar to each other. An increase of the temperature in both figures 3 and 4 at $\rho_{\text{pol}} > 1.1$ is caused by the shinethrough effect [17] and is not physical.

The fact, that the differences in the triggering profiles for type-I and small ELMs are vanishingly small and the profiles themselves are too scattered, suggests that there could be another parameter which controls the triggering of a particular ELM type. The parameter can be a coupling between the ELM eigenmodes with the perturbation field caused by B-coils, which directly changes the plasma stability without significant impact on the kinetic profiles. This is similar to the results obtained on D-IIID [18].

3.3 Data representation

Raw 2D ECEI data (Fig. 2b) are not very convenient to show and to analyse. A more convenient way of representing ECEI data is to separately plot the

vertical chords, where the studied mode activity is most pronounced, as a function of time. In Fig. 2d) one vertical chord just inside the separatrix is represented in such way, showing on the left a type-I ELM onset, and on the right a small ELM. In this representation the rotation of temperature fluctuations are clearly seen as a sequence of inclined lines. However, it should be noted, that ECEI system measures electron temperature in the laboratory frame, not in the plasma frame. The laboratory frame is a sum of the fluctuation velocity itself and the plasma $E \times B$ rotation velocity: $V_{\text{Lab}} = \omega/k + V_{E \times B}$. In this paper the terms 'fluctuation velocity' or 'mode velocity' will be used for the velocity in laboratory frame.

It is known that the mode structure of both type-I ELMs and small ELMs can vary significantly from one ELM cycle to another during a single discharge without noticeable changes in plasma parameters [19]. Thus, in order to pick out general features, common for the ELMs in a particular regime, the averaging over multiple ELMs is applied. In the following subsections a FFT for both time and space domains will be used as a convenient tool to average the data.

3.4 Mode localization

With 2D ECEI the position of the temperature fluctuations associated with type-I ELM onsets and small ELMs can be determined. For each of the 128 ECEI channels a spectrogram is built, similar to the ones in Fig. 2e (on the left a spectrogram for a type-I ELM is shown, while on the right - for a small ELM). When an ELM crash occurs, a clear broadband signal in the frequency domain is seen, which differs for different channels, as they are at different plasma positions. One way of quantifying the intensity of an ELM crash is to integrate the signal over a frequency band (an example of such integration from 12 to 70 kHz is shown in Fig. 2f) and to find the maximum on the obtained integral spectral amplitude. This maximum characterises mode strength at the moment of the ELM crash, seen by a particular ECEI channel. Averaging such maxima for each ECEI channel over ELMs gives a 2D spatial distribution of temperature fluctuations related to ELM crashes.

In Fig. 5a the distribution is shown for type-I ELM onsets before the transition to the small ELM regime (phase I), in Fig. 5b during the transition (phase II, these phases of the shot #26080 are indicated in Fig. 1). Fig. 5c represents the fluctuation intensity as a function of normalized radial magnetic flux coordinate ρ_{pol} . Here the flux coordinate ρ_{pol} is the square-root of the poloidal flux normalized in such a way, that it is zero on the magnetic axis and one on the separatrix. The maximum intensity in both cases, before and after the transition, is seen in a narrow band of ~ 2 cm in between

Figure 5: Mode localization of type-I ELM onsets before (a) and during (b) the transition. The black lines indicate the flux surfaces at $\rho_{\text{pol}} = 0.950, 0.975, 1.000, 1.025$ and 1.050 from left to right. c) Average intensity over vertical chords, built on the base of the plots 'a' and 'b' with red and black circles correspondingly. Solid red and black lines indicate averaged profiles. As seen in 'a' and 'b', temperature fluctuations related to type-I ELM onsets in both cases (before and during the transition) are localized between $0.975 \leq \rho_{\text{pol}} \leq 1.025$.

of $0.975 \leq \rho_{\text{pol}} \leq 1.025$, which indicates that the fluctuations are mostly localized in the pedestal region (the localization of the pedestal top is found in subsection 3.2: $\rho_{\text{pol}}^{\text{pedtop}} \sim 0.95 - 0.97$). It should be noted, that the separatrix can slightly shift its position from one ELM to another, as well as during one particular ELM. The position of the vertical ECEI chords depends on the toroidal magnetic field and is not fixed to a certain ρ_{pol} , therefore the position of the fluctuations indicated in Fig. 5 can not be precise.

The comparison of the plots in Fig. 5 allows to conclude, that type-I ELMs do not change their spatial intensity distribution during the transition. Also, this spatial analysis shows that it is enough to take data just from a vertical

chord close to $\rho_{\text{pol}} = 1.000$ to analyse type-I ELM onset modes due the fact that most part of the power of the fluctuation is localized there. This chord is shown in Fig. 2c and marked as chord #5. Since the separatrix has a curvature, the points in the vertical chord have different ρ_{pol} . The variation of ρ_{pol} in the points along the chord can reach up to 0.065 (for the lowest channel), however, most of the channels of chord #5 have variation in ρ_{pol} less than 0.025, which allows them to see strong activity.

Figure 6: Mode localization of small ELMs before (a) and during (b) the transition (normalized plots). The black lines indicate the flux surfaces at $\rho_{\text{pol}} = 0.950, 0.975, 1.000, 1.025$ and 1.050 from left to right. c) Average intensity over vertical chords built on the base of the plots 'a' and 'b' with red and black circles correspondingly. Solid red and black lines indicate averaged profiles. Similar to the case of type-I ELM onsets, temperature fluctuations related to small ELMs in both cases (during and after the transition) are localized between $0.975 \leq \rho_{\text{pol}} \leq 1.025$.

In the same manner as for type-I ELMs, the spatial analysis is applied to the temperature fluctuations associated with small ELMs. Figure 6 shows the

results for the small ELMs during and after the transition. The fluctuations in the case of small ELMs, as for type-I ELM onsets, are mostly localized in the same narrow band between $0.975 \leq \rho_{\text{pol}} \leq 1.025$ and their position does not change during the transition.

3.5 Mode velocities

Now, as the position of the modes, leading to ELM crashes, is known ($0.975 \leq \rho_{\text{pol}} \leq 1.025$), a more detailed analysis can be done. In this subsection the velocity of ELM preceding modes is considered. A 2D FFT is applied to type-I ELM onsets and small ELMs to see how they change during the transition to the small ELMs regime.

Figure 7: 2D FFT of type-I ELM onsets before (left) and during (right) the transition to the ELM mitigated regime with corresponding mode velocities (below). Positive velocities correspond to the electron diamagnetic drift direction in the laboratory frame. The inclination on the upper plots corresponding to a velocity of 5 km/s is marked with the white lines.

As seen in Fig. 7a, a standard 2D FFT plot includes both positive and negative half-planes which are mathematically symmetric. Therefore, it is enough to consider only the half-plane of positive frequencies. Considering it, positive values of wave-numbers correspond to mode rotation in the electron diamagnetic drift direction. The inclination of the distribution in the 2D FFT plot gives information on the velocity in the laboratory frame ($V_{\text{Lab}} = \omega/k + V_{\text{EXB}}$). As reference, the $V = 5 \text{ km/s}$ line is plotted.

The width of the 2D FFT windows for the analysis is chosen as $750 \mu\text{s}$ in the time domain (which equals to 150 time points of ECEI data at a sampling rate of 200 kHz) and $\sim 40 \text{ cm}$ in the space domain (which corresponds to 16 points, representing each line of sight of the ECEI). The vertical chord is taken, corresponding, according to the settings of the shot #26080, to the radial position around $0.975 \leq \rho_{\text{pol}} \leq 1.025$. The 2D FFT is applied separately to the type-I ELM crash onsets and to the small ELMs (Fig. 2a, regions are marked with green and red correspondingly) and averaged over all ELMs in the time ranges as defined in Fig. 1.

In Fig. 7 three dark blue vertical bands are seen, which correspond to filtered out frequencies: 0 kHz (corresponding to slow changes of the temperature), and $\pm 71 \text{ kHz}$, corresponding to diagnostic noise. The 2D FFT plot can be interpreted in terms of mode velocities, where the steeper a distribution is, the lower is the corresponding velocity. The shift of the wings of the distribution from zero (better seen in Fig. 8) indicates that none of both velocity terms is zero. Before the transition to the ELM mitigated regime the distribution in the figure is broader: it likely consists of two dominating mode velocities: $\sim 1 \text{ km/s}$ and $\sim 5 \text{ km/s}$. Whereas during the transition the mode with the velocity of 5 km/s becomes dominant, the distribution narrows and a bit extends to higher frequencies and wave-numbers.

Based on an angular projection of the 2D FFT plot, the mode velocities can also be plotted explicitly, as is done in the bottom plots of Fig. 7. The amplitude on the velocity plot during the transition increases, which just indicates the fact, that the distribution became more elongated in the direction of higher frequencies and wave-numbers.

In the same manner, the evolution of the small ELMs is presented in Fig. 8. There are some differences in the 2D FFT appearance between type-I ELM onsets and small ELMs. Small ELMs have one clear dominant mode velocity, corresponding to $\sim 6 \text{ km/s}$, which does not significantly change over the transition. The distributions for small ELMs extend to larger wave-numbers and frequencies than the distributions for type-I ELMs. This elongation to larger k -values and frequencies suggests, that smaller size fluctuations appear.

Figure 8: 2D FFT of small ELMs before (left) and after (right) the transition with corresponding velocities (below). Positive velocities correspond to the electron diamagnetic drift direction in the laboratory frame. The inclination on the upper plots corresponding to the velocity of 5 km/s is marked with the white lines.

A possible underlying mechanism, explaining why the distributions for small ELM modes extend to larger wave-numbers is following. As the density increases, the collisionality also increases which reduces the bootstrap current [20]. As the consequence, the mode becomes more ballooning-like, thus, the most unstable mode number increases [21] which corresponds to the higher k -values, seen in the case of small ELMs.

3.6 Conditionally averaged spectrograms

In this subsection the frequency evolution of the modes across an ELM will be studied. As before, the vertical chord is taken, which corresponds to the strongest mode activities, and a spectrogram (such as in Fig. 2e) is built

for each of the channels in the chord. Then, the spectrograms for each channel are averaged, resulting into one plot. To increase the quality of the data, conditional averaging over multiple ELMs is used, which allows to see the behaviour of an 'average' ELM crash. First, all the ELMs are divided into the groups according to the shot phases (see Fig. 1) and types (type-I ELMs / small ELMs). In each group there are more than 40 ELMs to average. Data samples of 4 ms length are chosen: 2 ms before and 2 ms after the crash, so the crash is in the middle of the data. In the next step, conditional averaging is performed for each group separately, resulting in Fig. 9.

Fig. 9 shows the following spectrograms: in the left column there are spectrograms for type-I ELMs, the right column has spectrograms for small ELMs. Each row corresponds to a discharge phase as defined in Fig. 1: the first one corresponds to the type-I ELMs phase (almost no small ELMs here are observed), the second to the transition phase, the third row corresponds to the mitigated ELMs phase (there are no type-I ELMs there), finally, the fourth one to the back transition. The vertical axis of each plot shows the frequency of the observed modes. It starts from around 12 kHz, cutting out relatively slow changes of the temperature. The horizontal axis denotes the time relative to the ELM crash.

Type-I ELMs during the transition have similar signature to type-I ELMs at the back transition, showing a long low frequency (20-30 kHz) tail (Fig. 9b,d). Small ELMs also have similar signature in the mentioned regimes, but, as opposed to type-I ELMs, have only short tails (Fig. 9f,h). Also some relatively low amplitude ~ 40 kHz oscillations are seen on all the spectrograms before the crash, which disappear afterwards.

The peak at the moment of crash (corresponding to 0 ms in Fig. 9) extends to the same frequencies in all the spectrograms, indicating that type-I ELM onsets and small ELMs at the moment of crash have the same frequency structure.

3.7 Conditionally averaged size of the structures

Using 2D ECEI it is possible to resolve fluctuations of a typical spatial size of several centimetres, occurring during ELM crashes. In this subsection the time evolution of the size of the structures, observed before (< 2 ms) and after ELMs, is studied.

As it was found in subsection 3.5, most of the modes rotate with a poloidal velocity around 5 km/s. This fact can simplify the analysis of the mode structures, if we look only at the modes, which rotate with this particular velocity. In order to do so, two different spectrograms for the same data set

Figure 9: Conditionally averaged spectrograms of ELMs, built on the base of vertical chord #5. The plots in the left column show spectrograms for type-I ELMs, while right column plots - for small ELMs. Times of averaging are shown in white in upper-left corners of the plots.

are built: the first one is as described in subsection 3.6, and the second one is built in the spatial domain, giving a wave-number as an output. In the case of the second spectrogram the Fourier transform is applied to the 16 points of the vertical chord of ECEI, where the fluctuations are the strongest. The same method of conditional averaging, as described in the previous subsection, is used to average the data over multiple ELMs. Then, dividing the data of the first spectrogram (ω) by the second one (k), the mode intensity for a fixed velocity ($V = \omega/k$) can be obtained.

Fig 10 shows different plots, presenting the data in a similar way as Fig. 9, by separating different ELM types (left column - type-I ELMs, right column - small ELMs), as well as different ELM regimes. On the ordinate axis the wave-numbers with corresponding frequencies at $V = 5$ km/s are indicated. The abscissa shows the time, relative to the ELM crash.

As it is seen from Fig. 10, for all cases (both types of ELMs, all the time regions), some structures exist prior to the crash, and their wave-number is around 0.5 cm^{-1} , which corresponds to $\sim 12.6 \text{ cm}$ in real space. This average size does not change prior to the crash, though, its distribution can become narrower closer to crash. At the moment of the crash the size of the structures increases to more than 20 cm in a short period of time of $\sim 30 \mu\text{s}$. Here one important difference between type-I ELMs and small ELMs arises:

Figure 10: Conditionally averaged mode number k , and frequency ω of ELM structures at $V = 5$ km/s. The plots in the left column show structure sizes for type-I ELMs, while right column plots - for small ELMs. Times of averaging are shown in white in upper-left corners of the plots.

after type-I ELM crash the size of the fluctuations continues to be large, while for small ELMs it fully recovers back to the initial size after about 1 ms. As the plots in Fig. 10 are velocity dependent, the fact that it are the structures, which change their size, but not the velocity, will be verified in subsection 3.9, where the conditionally averaged velocity is investigated. The highest mode amplitudes are seen for small ELMs in the mitigated regime. The reason for this is that after the transition to the small ELM regime, there are always some background temperature fluctuations present, so-called 'inter-ELM mode' [9]. The inter-ELM mode will be discussed in more details in subsection 3.8.

Mode numbers, corresponding to the wavenumbers, shown in Fig. 10, can be estimated. As it was shown in the subsection 3.4, the modes are localized in the region of $0.975 \leq \rho_{\text{pol}}$; according to the equilibrium calculations, the rational q surface closest to $\rho_{\text{pol}} = 0.975$ is $q_{0.98} = 6$ ($q_{0.95} \sim 5.7$ for the whole discharge). Generally speaking, the poloidal angle θ do not coincide with the poloidal angle of the magnetic field lines θ^* , and, in order to correct this, straight magnetic field line approximation [22] is applied, giving the ratio $d\theta/d\theta^* = 4.20$ for the desired surface $q_{0.98} = 6$ at LFS at the midplane.

Another assumption, which allows to obtain the mode numbers, is that the perturbations are elongated along the magnetic field lines. For the type-I ELMs in the whole discharge and the small ELMs in the transition phases (forward and back) the estimated poloidal mode numbers $m = 96 \pm 18$ and corresponding toroidal mode numbers $n = 16 \pm 4$. The error margins are estimated from the mode numbers, corresponding to the closest to $q = 6$ rational flux surfaces: $q_{0.960} = 11/2$ and $q_{0.985} = 13/2$, also taking into account the spread in the wavenumber k in the range of $0.45 \leq k \leq 0.55$.

Figure 11: Conditionally averaged wave number k , and frequency ω of small ELM structures at $V = 5$ km/s for the back transition. The left plot shows structure sizes for the beginning of the back transition (4.5 s.), while the right plot shows the end of it (5.7 s.).

Fig. 11 is the back transition phase for the small ELMs. In the back transition the background fluctuation is disappearing, which becomes visible if the averaging is done in two separate time-windows. At the beginning of the back transition (fig. 11a) the background temperature fluctuation, the inter-ELM mode, is strong and has a broad distribution in the frequency domain, while later on (fig. 11b) it has almost completely gone. The inter-ELM mode is also mostly absent in the pure type-I ELM phase, which makes the presence of the mode to be one of the main differences between type-I ELMs and mitigated ELMs regimes.

3.8 Inter-ELM mode

As shown in subsection 3.7, one of the differences between the ELM mitigated phase and the type-I ELM regime is the constant presence of the background fluctuations during the ELM mitigated phase, which only episodically appears at the type-I ELM phase. These fluctuations are described in [9], where they are called an 'inter-ELM mode'.

In Fig. 12, the period between two small ELMs in the mitigated regime is plotted. The first small ELM occurs at 4.259 s., the second one at 4.2682 s. and almost continuous activity is seen between them. Half a millisecond after,

Figure 12: An inter-ELM activity between two small ELMs in the mitigated phase. Upper plot shows the ECEI data of one vertical chord as a function of time, bottom plot shows the spectrogram for the same time range.

the first ELM the frequency recovers, which is typical for small ELMs (as shown in subsection 3.7), and reaches 50 kHz. This is different from type-I ELMs, where the frequency is not recovered for at least several milliseconds.

In Fig. 10g, corresponding to mitigated ELMs regime, the distribution of wavenumbers is broader, than in other regimes, especially in comparison with the pure type-I ELMs regime (fig. 10a). Broader distribution of wavenumbers originates from the presence of inter-ELM mode in mitigated ELMs regime. Fig. 11a shows the beginning of the back transition, where there is still a presence of the inter-ELM mode, and thus, the distribution of the wavenumbers is also broad there, whereas after the back transition to the type-I ELMs regime (fig. 11b) the inter-ELM mode disappears. The broader distribution in wavenumbers in case of inter-ELM mode causes broader distribution of mode numbers, rather than those for ELM onsets. The inter-ELM mode has typical values of mode numbers of: $m = 99 \pm 47$ for poloidal and $n = 17 \pm 9$ for toroidal, taking into account the same assumptions as in subsection 3.7. The average values of the mode numbers here are similar for those of ELM onsets.

In [23] inter-ELM mode is observed in type-II ELMs regime, with its maximum in frequency around 40 kHz. There, when the inter-ELM mode occurs between two ELMs in the type-I ELMs regime, it increases the time needed for the next type-I ELM to occur and, thus, can be a mechanism of regulating the pedestal stability [9]. In the small ELM regime the inter-ELM mode is constantly present in the plasma, merging with small ELMs, when they occur. According to subsection 3.2 for the current shot it is not possible to deduct whether the presence of the inter-ELM mode affects the kinetic profiles.

3.9 Conditionally averaged mode velocities

In this subsection the time evolution of the mode velocity, occurring during ELM crashes, is studied.

For each ELM data, covering a time range from 2 ms before the crash to 2 ms after is taken. This data is then divided into samples of $80 \mu\text{s}$ and in each of them a 2D FFT is performed. In the same way, as in subsection 3.5, the velocity is obtained from the 2D FFT. Positive values of the velocity correspond to the mode rotation in the electron diamagnetic drift direction in the laboratory frame.

Figures 13 and 14 show the conditionally averaged mode velocity for type-I and small ELM crashes correspondingly during the transition phase to the small ELMs regime. Fig. 13 additionally shows 2D FFT at certain moments of the averaged crash. Before the crash the modes with a velocity around 5-6 km/s are seen (Fig. 13a). At the ELM onset modes have a broader velocity distribution (2-10 km/s) and become more intense (Fig. 13b). Immediately after the crash, as seen in Fig. 13d, some modes with the velocity in ion diamagnetic drift direction appear (which corresponds to negative values of the velocity on the plot) and continue to exist even further (Fig. 13e).

Figure 13: Conditionally averaged mode velocity behaviour of type-I ELM crash and 2D FFTs. After the crash the velocity mostly stays at -1 km/s. The inclinations on plots (a)(b)(d)(e) corresponding to a velocity of 5 km/s are marked with the white lines.

Figure 14: Conditionally averaged mode velocity behaviour of small ELM crash. After the crash the velocity continues to stay at around 6 km/s.

For both small and type-I ELMs the mode velocity falls down at the moment of the crash from 5 – 6 km/s to zero or negative values. This drop in velocity occurs in a time of tens of microseconds. But there is a principal difference between type-I ELM crashes and small ELM crashes: after a type-I ELM crash the velocity drops and continues to stay below zero (Fig. 13), whereas after a small ELM crash, the mode velocity returns to the initial value (Fig. 14).

Returning back to the analysis in the subsection 3.7, looking at the plots of small ELMs in Fig. 10 and taking into account Fig. 14, one can verify, that what really changes after small ELM crashes is the size of the structures, while the velocity stays at the same level.

Another interesting feature, which comes out after type-I ELMs and mostly appears at the transition to small ELMs phase, is a velocity oscillation: after the velocity falls down to the negative values of 1 – 2 km/s at the crash, in 200 μ s it becomes positive, and can reach initial rotation velocity of 5 – 10 km/s, but then becomes negative again. Not every type-I ELM has such a feature, but one of three, that is why this tendency is not clearly seen on the averaged plot in Fig. 13, but becomes evident if ELMs are plotted separately, like in Fig. 15a. There can be several periods of such oscillations, which are observed only for type-I ELMs.

After an ELM crash the separatrix slightly moves inside, while the position of the ECEI channels stays the same, which affects the ECEI measurements and can cause a diagnostic artifact. If the separatrix moves deep inside, such that ECEI channels see the outer plasma region, where the radial electric field is positive, then the observed mode velocity can become negative.

Fig. 15b, c, d show the equilibrium for the moments of time before the ELM, at the moment of the crash and after the ELM. After the crash (Fig. 15d) the separatrix shifts 0.5 – 1 cm inside the plasma, which is comparable with the radial size of an ECEI channel (~ 1.5 cm). As there are no negative velocities observed in the next outer channel, the oscillatory behaviour of the modes is

Figure 15: Mode velocity of one type-I ELM and corresponding equilibrium. (a) Velocity oscillation is observed after the crash ($t = 1.6599$ s.). (b)(c)(d) Equilibrium at the moments of time 1.6594, 1.6600 and 1.6610 s. correspondingly. The position of separatrix is marked with the bold red line, the shaded area indicates the wall. The cross-hairs are guiding eye to the location at the maximum of the separatrix to make its displacement more visible.

not a diagnostic's artifact, but is a real phenomena.

4 Discussion

There are many similarities between type-I ELMs and small ELMs. Some of the features, which are similar, do not change along the transition to a small ELMs regime: both modes are localized close to the separatrix, in the same narrow region of ~ 2 cm, the peak of mode intensity for both types of crashes is the same. Also they have the same dominant mode velocity around 6 km/s in the laboratory frame, which is probably dominated by $E \times B$ rotation velocity at this radial position. At the very moment of a crash, in both cases the rotation velocity falls to 1 km/s and its direction changes to

the direction of ion diamagnetic drift. Prior to both types of crashes, some modes with a frequency of 40-50 kHz are seen.

There are also some features which are different for small ELMs and type-I ELMs. After a type-I ELM crash the mode number of the fluctuation structures becomes lower and stays on that level for more than 2 ms, whereas for small ELMs a less pronounced decrease in mode number is observed, quickly recovering to the initial level. Related to this, the velocity of the temperature fluctuations for type-I ELMs and small ELMs also behaves differently: after a small ELM crash most of the modes continue to rotate with the same velocity as before the crash, while for type-I ELMs the velocity does not recover fast after the drop to the negative values. Moreover, for type-I ELMs at the transition phase some velocity oscillations are seen immediately after the crash, which is never observed for small ELMs. This could be caused by oscillations of the radial electric field, which affects the $E \times B$ drift and, thus, the velocity. The modes, observed at the transition phase prior to both types of ELMs at 40-50 kHz, disappear immediately after the crash in case of type-I ELMs, while for the small ELMs they remain. These modes are identified as inter-ELM modes [3][9][23].

The back transition from the small ELM regime to the type-I ELM regime looks like a reversed forward transition, so no hysteresis is observed.

The velocity of small ELMs considered here, which is 6 km/s, is the same as the type-II ELMs analysed by J. Boom in [23]. However, the type-II ELMs in [23] are localized at $\rho_{\text{pol}} = 0.94$, while here they occur at $0.975 \leq \rho_{\text{pol}} \leq 1.025$ and do not show the 'off-axis' behaviour as observed in [23]. Different radial position of the modes can be explained by other shape of the q -profile, which results in different location of resonant surfaces.

Mode numbers, and mode velocity always decrease during the crash, and both continue to be small for type-I ELMs after crash. The mode activity, which leads to ELM crash, has mode numbers lying in the range of $m = 96 \pm 18$, $n = 16 \pm 4$ for both type-I and small ELMs. The range of the observed mode numbers suggests, that the peeling and ballooning modes for both types of the ELMs are coupled [21]. Taking into account the observations, one can say, that both the type-I ELMs and small ELMs observed on AUG have the same nature and evolve over the transition together.

An important feature of the transition to the mitigated ELMs regime is a continuous inter-ELM mode in between ELMs, which in other regimes appears only episodically. This inter-ELM mode can last up to the coming ELM crash, merge with it, and still be there immediately after the crash. This is reminiscent of the transition from type-I ELMs to type-II ELMs, described in [9]. The frequency of the inter-ELM mode can vary inside of one ELM

cycle in the range of 40 kHz to 60 kHz and its mode numbers are spread in the range of $m = 99 \pm 47$ for poloidal and $n = 17 \pm 9$ for toroidal mode numbers.

The analysis did not show significant differences in the kinetic plasma profiles for the moments when both type-I and small ELMs are triggered. In this case the stability of the modes can be changed directly by the coupling between the ELM eigenmodes with the perturbation field, caused by B-coils. This is similar to the results obtained on D-IIID [18].

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References

- [1] H. Zohm *Plasma Phys. Control. Fusion* **38** (1996) 105
- [2] ITER Physics Basis Editors et al. (1999) *Nucl. Fusion* **39** 2137
- [3] E. Wolfrum *Plasma Phys. Control. Fusion* **53** (2011) 085026
- [4] N. Oyama et al. *Plasma Phys. Control. Fusion* **48** (2006) A171
- [5] T. Evans et al. *Phys. Rev. Lett.* **92** (2004) 235003
- [6] W. Suttrop et al. *Phys. Rev. Lett.* **106** (2011) 225004
- [7] W. Suttrop et al. *Plasma Phys. Control. Fusion* **53** (2011) 124014
- [8] E. Wolfrum et al. Pedestal properties of mitigated ELMy H-modes at high density at ASDEX Upgrade. *Proc. 41th EPS Conf. on Plasma Physics* (Berlin, Germany, 23-27 June 2014) P2.006
- [9] I.G.J. Classen et al. *Nucl. Fusion* **53** (2013) 073005
- [10] Y. Liang et al. *Plasma Phys. Control. Fusion* **49** (2007) B581-B589
- [11] M.E. Fenstermacher et al. *Phys. Plasmas* **15** (2008) 056122

- [12] I.G.J. Classen et al. *Rev. Sci. Instrum.* **81** (2010) 10D929
- [13] J.E. Boom et al. *Nucl. Fusion* **51** (2011) 103039
- [14] G. Bekefi. Radiation processes in plasmas (1966) John Wiley & Sons, New York, USA
- [15] R. Fischer et al. *Fusion Science and Technology* **58/2** (2010) 675-684
- [16] P.C. Stangeby. The Plasma Boundary of Magnetic Fusion Devices (2000) Taylor & Francis, New York, USA
- [17] S.K. Rathgeber et al. *Plasma Phys. Control. Fusion* **55** (2013) 025004
- [18] T.E. Evans et al. *Nucl. Fusion* **45** (2005) 595-607
- [19] A.V. Bogomolov et al. Variation of ELM signatures observed by ECE Imaging on ASDEX Upgrade, *Proc. 40th EPS Conf. on Plasma Physics* (Helsinki, Finland, 1-5 July 2013) P4.114
- [20] C.E. Kessel. *Nucl. Fusion* **34** (1994) 1221
- [21] A.W. Leonard. *Phys. Plasmas* **21** (2014) 090501
- [22] M. Schittenhelm and H. Zohm *Nuclear Fusion* **37** (1997) 1255
- [23] J.E. Boom et al. *Nucl. Fusion* **52** (2012) 114004