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Citation for published version (APA):
Bogomolov, A. V., Classen, I. G. J., Boom, J. E., Suttrop, W., de Vries, P. C., Donne, A. J. H., Tobias, B. J., Domier, C. W., & Luhmann, N. C. (2013). Variation of ELM signatures observed by ECE Imaging on ASDEX Upgrade. In *40th EPS Conference on Plasma Physics, EPS 2013* (Vol. 2, pp. 946-949). European Physical Society (EPS).

Document status and date:
Published: 01/01/2013

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Variation of ELM signatures observed by ECE Imaging on ASDEX Upgrade

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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 steady state reactor operation can cause intolerable erosion of the first wall materials. Thus, study of the ELMs is needed in order to better control these events in future devices.

The ECE Imaging (ECEI) diagnostic at ASDEX Upgrade (AUG) is a 2D diagnostic which consists of a linear array of 16 detectors, each of which acts as a standard (1D) ECE radiometer. This diagnostic allows the visualization of various MHD instabilities occurring in the plasma with high temporal and spatial resolution [1]. The ECEI observational area of ~10x40cm is positioned at the low field side (LFS), centered vertically on the mid-plane and radially covers the separatrix. This allows the observation of the 2D electron temperature evolution of the ELM cycle in detail [2].

A large database has been created with several hundred discharges for which ECEI data at the edge were available. The database contains pulses with a broad range of plasma parameters, such as, the pedestal temperature (up to 2keV), density (up to $8 \cdot 10^{19}$ m^{-3}), or the edge collisionality ν^* (between 0.1 and 4). The ECEI analysis provides information on the signature of the ELM, such as the mode structure, the duration of mode activity until the crash and the poloidal rotation velocity. The focus of this study is to provide a broader characterization of ELM crashes and their dependencies on plasma parameters.

The whole type-I ELM cycle on AUG typically lasts 10-20 ms and can be divided into three phases. The first phase is the ELM onset mode which consists of fast poloidally rotating (5-12 km/s) modes leading to the ELM crash. Often, the poloidal velocity increases as the mode develops. This phase lasts ~100μs [3]. The second phase is the ELM crash itself in which the sharp decrease of the temperature at the edge occurs and some localized structures ('filaments') of higher temperature appear outside of the separatrix [2]. An ELM crash usually lasts about 2 ms. After the ELM crash has ended the third phase starts, which in terms of ECEI is characterized by a recovery of the temperature due to a re-establishment of the electron transport barrier (ETB) [2]. Often, in between ELM crashes the so-called inter-ELM mode appears. These modes are more pronounced off-midplane and typically have velocities of 2-4 km/s. It should be noted that not all the ELM cycles show inter-ELM modes [2]. All the observed MHD modes primarily rotate in the electron diamagnetic drift direction [3]. This work will characterise and quantify the instabilities seen prior to the ELM crash in all discharges for which ECEI data were obtained on AUG. It will look into variations with pedestal parameters as well as differences within single discharges.

2. Methodology

Figure 1a gives an example sequence of 2D images of an ELM onset mode prior to the crash (discharge parameters: B_t = 2.5T, I_p = 1 MA, P_{NBI} = 7.5MW and P_{ECRH} = 0.75 MW). It is easier to study the poloidal dynamics of the modes plotting only one vertical chord as the function of time (Fig.1b). Now all MHD activity, such as inter-ELM modes or ELM onset modes become visible in the plot as a sequence of inclined lines. To quantify the intensity of the MHD activity, the spectrogram of a line-of-sight (LOS) is calculated (Fig.1c) and the resulting spectral power above a noise threshold level is integrated over all frequencies (Fig.1d). The noise threshold level was taken as one standard deviation of the data from the mean value of the spectrogram. After performing these operations it is evident where the MHD activity (inter-ELM mode and onset mode) overcomes the noise level (Fig.1d) and the time duration up to the time of the crash can be determined. Considering the plot of integrated MHD power (Fig.1d) the ELM onset mode duration is defined as the time needed for MHD activity to rise from the noise level up to its highest value, corresponding to the beginning of the ELM crash (after this moment the temperature starts to decrease).

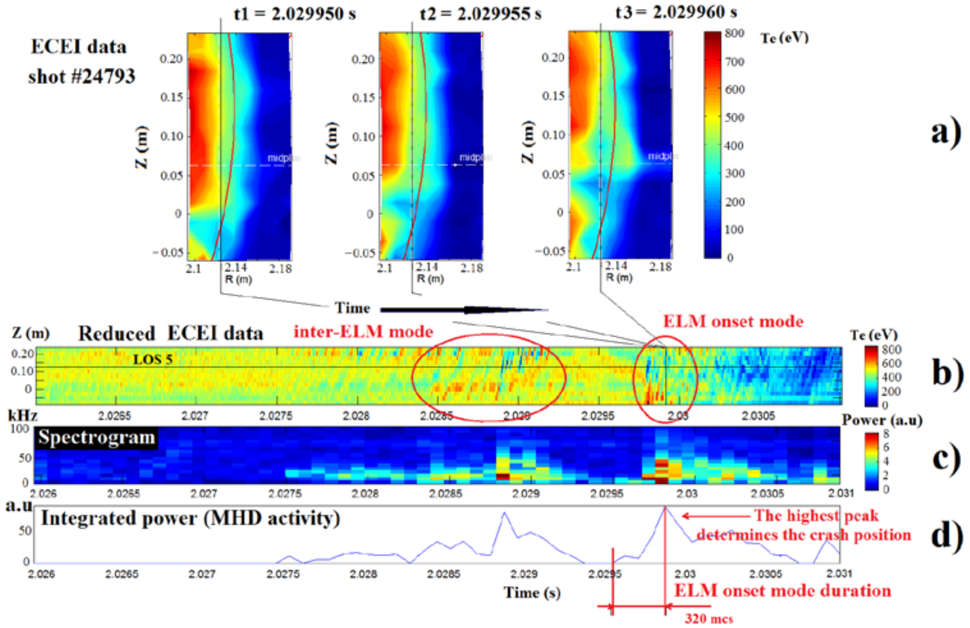

Figure 1. Determination of ELM duration. A) 2D T_e in three consecutive moments of time. A dip in T_e propagating upwards (electron diamagnetic direction) is seen. B) One vertical LOS of the initial 2D T_e is plotted versus time. The ELM onset mode looks like a set of inclined lines here. C) Spectrogram of one of the LOSs showing two different activities: inter-ELM mode and ELM onset mode. D) Spectral intensity integrated over all frequencies and with the noise cut out. The ELM onset mode duration is defined as the rise of the MHD activity from zero to its maximum value.

To obtain the quantitative characteristics of MHD activity (such as velocities, frequencies and mode numbers) a 2D fast Fourier transform (FFT) is applied to the period of mode activity as defined above. This is done over the radial average of those ECEI signals that lie within the separatrix, i.e. where the mode develops.

The raw 2D FFT spectrum (Fig.2) can quickly give a qualitative impression concerning the characteristics of the MHD activity. The quantification of mode velocity, frequency and wave number is the question for future studies.

3. Results

To study the variation of ELM characteristics automated analysis of the duration of MHD activity was applied to approximately 100 ELM cycles in several plasma discharges; in each discharge only the period with constant plasma parameters was taken. It was found that the durations and the signatures of MHD activity can vary significantly from one ELM cycle to another during a single discharge without noticeable changes in the plasma parameters. In particular, it was found that at low collisionality ($\nu^* < 0.5$) and high pressure the inter-ELM behaviour changes, with some modes moving opposite to the electron diamagnetic drift direction, exhibiting much lower velocities (less than 1 km/s) than usual.

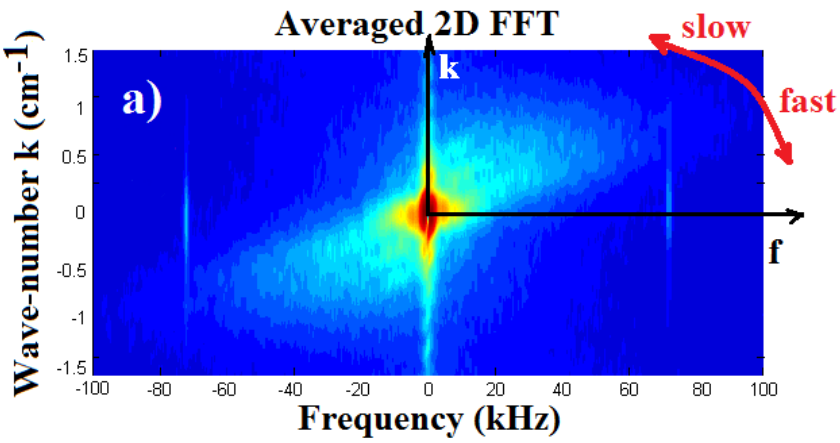

Figure 2. 2D fast Fourier transform applied to the data from Fig.1b (ELM onset mode region). The inclination of the cyan cloud gives information on the mode velocity (V=ω/k). Negative values correspond to mode rotation opposite to the electron diamagnetic drift direction.

It was found that the mode activity does not always develop in the same way. Three distinct types of mode activities were observed (Fig.3). In the first type, the inter-ELM mode is detached from the ELM onset mode. In other words, after the inter-ELM mode disappears (typically 1ms), there is a period (lasting around 1 ms) where no MHD activity exists before the ELM onset mode starts to grow leading to the ELM crash (Fig.3a). The second type of earlier mode activity smoothly merges into the ELM onset mode, making them hard to distinguish from each other (Fig.3b). The last type was identified as the so-called 'Edge Snake' [4]. It is seen by ECEI as sharp highly periodical dips in the temperature which appear every 500μs, after which the ELM onset mode appears and triggers the ELM crash (Fig.3c). Spatially, this Edge Snake mode is located within the separatrix in the region of high temperature and density gradients. The Edge Snake consists of a radially and poloidally localized current wire, in which the temperature and density profiles flatten [4].

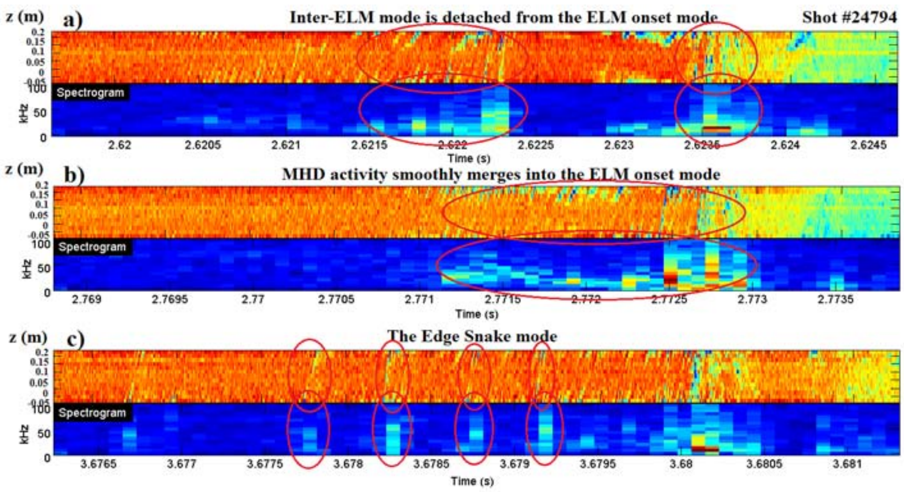

Figure 3. Different types of MHD activities: ECEI data and its spectrogram. c) Inter-ELM mode is detached from the ELM onset mode. a) Inter-ELM mode smoothly develops to the ELM onset mode, a continuous activity is seen on the spectrogram below. b) Edge Snake mode which is characterized by small periodical dips on T_e (or bursts on the spectrogram), and is also detached from the ELM onset mode.

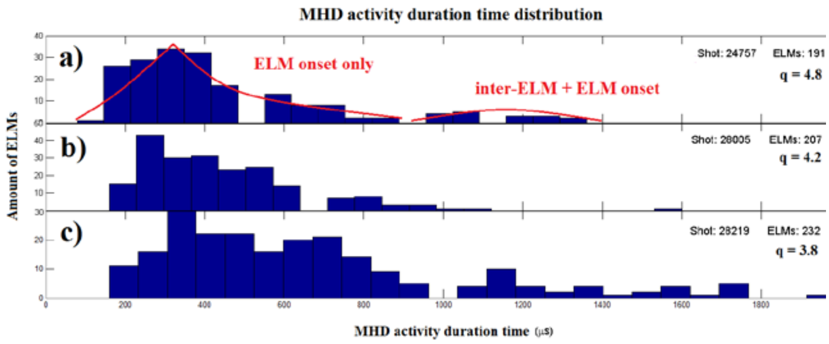

Figure 4. Inter-ELM and ELM onset modes duration distribution inside of two similar discharges, which mainly have the difference in q95. The mean values for the first peaks are slightly different, the distribution for #24757 has the second peak, while the shot #28219 has only a pronounced long tail and the shot #28005 almost does not have it.

Because of the large variation of ELM parameters within a single discharge, dependencies with main plasma parameters are best done by comparing the distribution of these parameters, obtained by the automated methods discussed in section 2. A subset of the database with parameters within the following range were analyzed: magnetic field $B_t = -2.5$ T, plasma current I_p varied in the range of $0.9 \leq I_p \leq 1.1$ MA, a safety factor $3.7 < q_{95} < 4.5$, heating by neutral beam injection of 7-10 MW and simultaneously by 750 kW of electron cyclotron resonance heating (ECRH). The edge collisionality ranged from $\nu^* \sim 0.4$ (#28005) to $\nu^* \sim 0.9$ (#24794)).

Figure 4 shows the change in the distributions of ELM duration for three discharges with different safety factor q_{95} indicating a longer (mean) duration at lower q_{95}. It should be noted that the distributions have often two maxima due to the definition of the 'ELM duration' and the fact that sometimes the inter-ELM merges into the ELM onset mode (Fig. 3b), i.e. giving longer duration when only the onset mode is considered alone.

4. Summary and outlook

The influence of ELM characteristics quantified with the methods above with changes in plasma or pedestal parameters can be studied. However, it was found that large variations existed with single discharges with constant plasma parameters. Hence, first insight in these variations is needed.

Three different types of MHD activity were observed. The parameters (mode velocities, frequencies and mode numbers) should be studied separately for each type of MHD activity. A similar ELM characteristics analysis described in [2] has been done for multiple ELMs and for several discharges. An algorithm for the determination of the ELM onset mode duration was developed. ELM characteristics vary considerably, even within one discharge with constant main plasma parameters, resulting in a distribution for key parameters like the ELM duration, mode frequency and wave number.

The distribution of MHD duration varies with plasma parameters which opens a door for future research.

5. Acknowledgments

This work, supported by the European Communities under the Contract of Association between EURATOM-FOM, was carried out within the framework of the European Fusion Program, with financial support from NWO, FOM and EURATOM. The views and opinions expressed herein do not necessarily reflect those of the European Commission. © Euratom 2011.

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