High spatial and temporal resolution FM-CW reflectometry to study pellet triggered ELMs at ASDEX Upgrade

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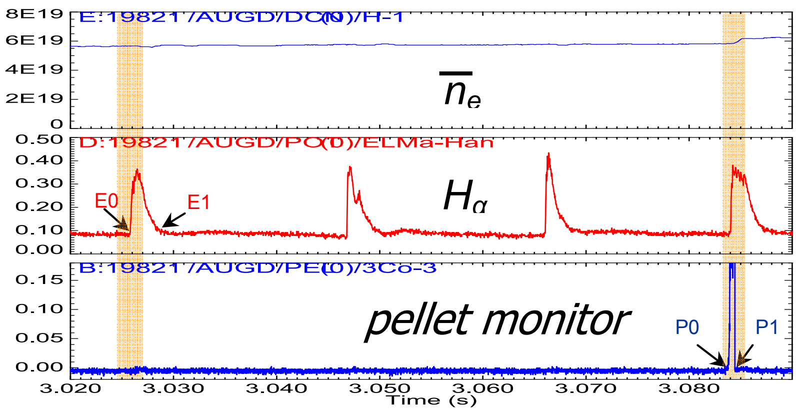
Introduction

The high-confinement mode (H-mode) is foreseen as the basic operation scenario for ITER. However, it drives transient, edge localized modes (ELMs), causing periodic expulsion of plasma energy and particles. In particular the type-I ELMs can generate large energy losses from the plasma, which can lead to unacceptably high power loads on first wall elements. ASDEX Upgrade is carrying out experimental studies to control the ELM frequency in order to mitigate them. The most successful technique was achieved triggering ELMs by cryogenic pellets that has also shown to be a promising tool to investigate ELM physics[1,2]. Reflectometry, due to its high temporal and spatial resolution, is a diagnostic specially suited for this type of experiments. For example, detailed profile measurements from reflectometry showed that intrinsic ELMs in ASDEX Upgrade start to evolve at the LFS[3]. The reflectometry analyses of pellet experiments, performed so far, were focused on the study of density profiles in the regions between ELMs, where profiles are not distorted by the ELM activity. Comparing intrinsic and triggered ELMs phases no significant differences were found. In order to better characterize the plasma behavior we extended the previous study to density changes during both types of ELMs. As during ELMs strong perturbations are usually present at the plasma edge, profile evaluation can be difficult, especially at the phase of inward particle and energy flux indicated by the peak of the H_α signal. For this reason we developed a new method to visualize in a simple and direct way the local profile changes, without the need to evaluate the density profile. The method uses the spectrogram of the plasma reflected signals derived from swept frequency data (basic information for density profile inversion) and

Fig. 1 – Average density, outer divertor H_α signal and pellet ablation monitor time traces for ASDEX Upgrade plasma discharge #19821



gives the temporal evolution of spectrogram slices centered at selected plasma densities. The ASDEX Upgrade FM-CW reflectometry system has 9 swept channels, 5 at the low field side (LFS) and 4 at the high field side (HFS), probing the plasma simultaneously. In order to have the best time resolution, all the channels were operated at the maximum repetition rate (sweep duration 25 μs, interval between sweeps 25 μs), corresponding to a total data acquisition window of 107.24 ms (limitation imposed by available system memory). Information at higher densities (up to $1.2 \cdot 10^{-20}$ m^{-3}) could be obtained also after the recent improvement of the W-band channel at the LFS.

Novel method to analyze local density variations

The new method is based on the time evolution of slices of the reflected signal spectrograms taken at selected density layers. The spectrograms, representing the spectral content of the reflected signals (over the entire probed plasma region), are obtained with the simultaneous operation of the different swept channels. They are the basic tool to extract the group delay for profile evaluation but display also the spectral features due to plasma density perturbations, namely due to ELMs. Using spectrograms from consecutive sweeps it is possible to track the temporal evolution of the local spectra at selected probing frequencies (=densities). To illustrate the method we present examples obtained in ASDEX Upgrade H-mode discharge #19821 (plasma current 1 MA, average density $8.8 \cdot 10^{-19}$ m^{-3}) where pellets were launched between 1.4 and 3.4 s with 5 Hz frequency and 240 m/s velocity. In fig. 1 are shown the time traces for average n_e, outer divertor H_α signal and the pellet ablation monitor signal between 3.020 and 3.090 s. The first three ELMs in this time window are intrinsic, the last one is triggered by pellet injection. An example of one of the spectrograms obtained for t=3.025725 s (sweep 736) is depicted in fig. 2; in red it is marked the slice of the spectrogram at 59 GHz (n_e=$4.3 \cdot 10^{-19}$ m^{-3}). The temporal evolution of that spectrogram slice obtained from sweeps 730÷765, corresponding to the time interval t=3.025515÷3.026740 s, is represented in fig. 3. The response of the selected plasma layer to the onset of the intrinsic ELM at $t_{0,H\alpha}$=3.025790 s can be clearly seen from the increase of the group delay starting at sweep 740 (t=3.025865 s). This indicates the inward movement of the density layer (away from the launching-receiving antenna) and therefore the density profile flattening caused by the ELM. Even if strong density perturbations occur during each ELM affecting the probing signals and making difficult profile evaluation, especially at the peak of the ELM, with the new method abrupt changes of density profile (group delay) during the complete ELM duration can be seen from slices of reflected signal spectrograms. To clarify the procedure, the density profiles corresponding to the sweeps indicated by three vertical dashed lines in fig. 3, sweep 736

Fig. 2 – Example of group delay spectrogram slice (#19821)

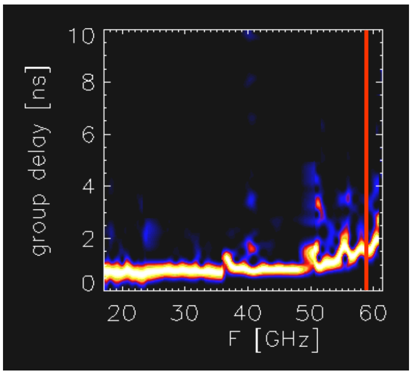
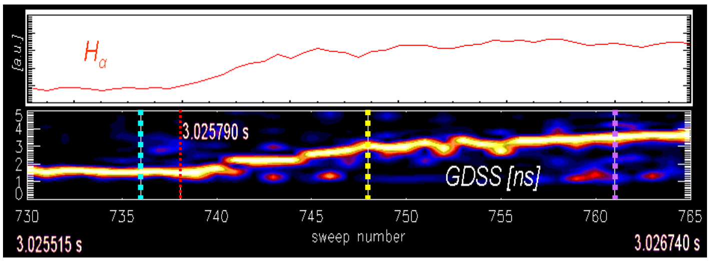


Fig. 3 – Temporal evolution of the HFS group delay spectrogram slice (GDSS) at 59 GHz (#19821)



(65 μs before the ELM), sweep 748 (355 μs after the ELM) and sweep 761 (810 μs after the ELM), are displayed in fig. 4, where the selected density layer is also indicated.

Profile changes due to intrinsic and triggered ELMs

In the following we present the results concerning the first ELM (natural) and the fourth one (triggered) shown in fig. 1. With E0 and E1 we define, respectively, the beginning and the peak of the H_α signal; with P0 and P1 we indicate the beginning and the end of the pellet ablation in the plasma. We have chosen eight frequencies (density layers) and computed the temporal evolutions of eight group delay spectrograms slices (GDSS) for the intrinsic and the triggered ELM at the HFS (shown in fig. 5). For the intrinsic ELM (left part of fig. 5) a clear inward movement is seen at plasma layers n_e=3.8·10^{-19} m^{-3} and n_e=4.3·10^{-19} m^{-3}, corresponding to probing frequencies F=55 GHz and F=59 GHz. For frequencies 66 GHz (n_e=5.4·10^{-19} m^{-3}),

Fig. 4 – HFS density profiles corresponding to vertical lines in fig. 3 (#19821)

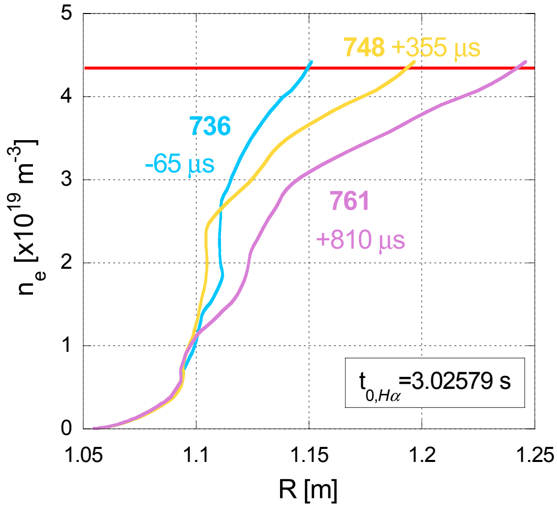
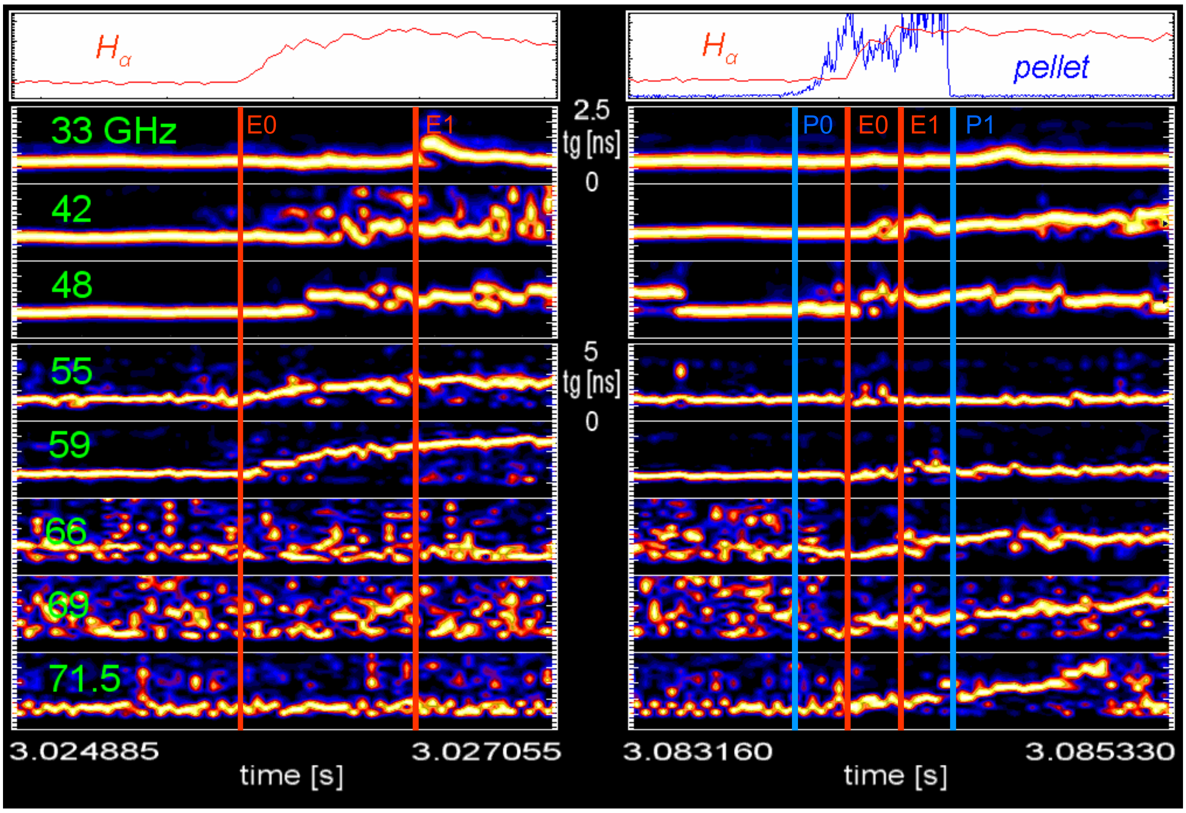


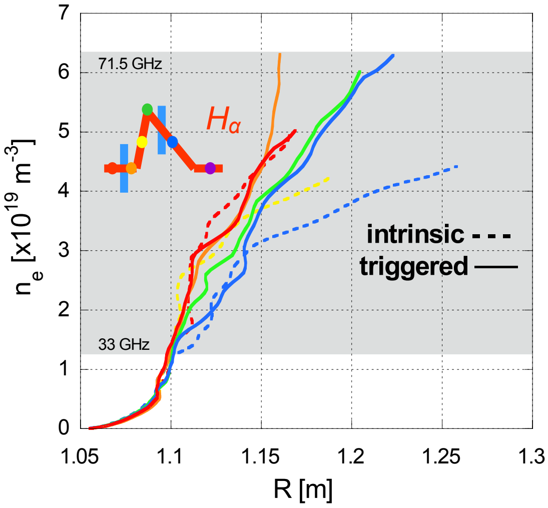
Fig. 5 – Temporal evolution of the GDSS for the intrinsic (left) and triggered (right) ELM at the HFS (#19821)



69 GHz (n_e=5.9·10^{-19} m^{-3}) and 71.5 GHz (n_e=6.4·10^{-19} m^{-3}) the reflected signal cannot be detected because the density is not sufficiently high to reflect the probing microwaves. At 71.5 GHz the detected spectrum corresponds to the noise base line of the heterodyne detection. In the case of the pellet triggered ELM, we first notice that the movements of the

plasma are shifted to higher frequencies (66, 69 and 71.5 GHz). We can see that just after the pellet injection resulting in the peaking of the density profile at the HFS, the entire V-band channel (50÷72 GHz) comes into operation. The GDSS plots also show how the density profile continues its flattening after the peak of the H_α signal, E1. In fig. 6 are shown the HFS density profiles corresponding to the main ELM phases. The plasma density profile is the same before the ELM and before the pellet injection (red line). Just after the pellet injection (orange line) the density peaking allows to measure the profile up to n_e=6.4·10^{-19} m^{-3}. In the phase after E1 the profile (blue line) is still flat but for the triggered ELM it is steeper; this is due to a double effect: the flattening due to the ELM and the density fuelling due to the pellet ablation. Phase between E0 and E1 (yellow line) and peak E1 (green line) are also depicted.

Fig. 6 – Temporal evolution of HFS density profiles during intrinsic and triggered ELMs (#19821)



Conclusions

The above study demonstrated that the new data analysis method has the advantage of a direct and simple evaluation (fully automatic). As it does not require the evaluation of the density profile, it is independent of any initialization procedure (O-mode operation only) or errors associated with X-mode (when X-mode is utilized to complement O-mode at the very edge). The method is very useful to track fast local profile changes and it can provide also the localization (in space and time) of density perturbations associated with fast plasma events, such as ELMs. It has the advantage that it can be used even when high resolution (25 µs) single sweep density profiles are distorted due to plasma turbulence. The first analysis, here presented, clearly demonstrates how reflectometry can contribute to the study of the dynamics of intrinsic and triggered ELMs. This study seems to indicate that the two types of ELMs are very similar but to answer definitively this question more investigation is needed. For example, it is important to detect where the triggered ELMs occur first, at HFS or at LFS. The analysis of the space time evolution of the plasma turbulence during the two types of ELMS is another relevant issue to be investigated with fixed frequency operation of reflectometry channels.

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