A new spectral analysis to study pellet triggered ELMs from broadband reflectometry at ASDEX Upgrade

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Introduction

The high-confinement mode (H-mode) is foreseen as the basic operation scenario for ITER. Unfortunately it usually 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 main plasma, which can lead to unacceptably high heat power loads on the first wall elements, especially on the divertor target plates. ASDEX Upgrade is carrying out experimental studies to control the ELM frequency by mean of an appropriate technique in order to mitigate them. The most successful one was achieved triggering ELMs by cryogenic pellets that has also shown to be a promising technique to investigate ELM physics[1]. Reflectometry, due to its high temporal and spatial resolution, is a diagnostic specially suited for this type of experiments. The ASDEX Upgrade FM-CW reflectometry system has 9 swept channels in K, Ka, Q, V and W frequency bands at the low field side (LFS) and in K, Ka, Q and V bands at the high field side (HFS), probing the plasma simultaneously. In swept mode these channels operate with a minimum repetition rate of 35 μs and in fixed frequency mode with a sampling rate up to 1 MHz. Previous reflectometry analyses of pellet experiments were focused on the study of density profiles (especially at LFS) 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 understand the plasma behavior it became clear that it was necessary to analyze also the density changes occurring during both types of ELMs. For example, it was previously demonstrated that intrinsic ELMs in ASDEX Upgrade start to evolve at the LFS[2] but no indications exist about the evolution of their triggered counterpart. Usually during ELMs strong perturbations are present at the plasma edge and profile evaluation can become difficult, especially at the peak of the ELM. For this reason it was necessary to develop a new method that could visualize in a simple and direct way detailed local profile changes, without the need to evaluate the density profile. The method uses the spectrogram derived from swept frequency data (basic information for density profile inversion) and gives the temporal evolution of spectrogram slices centered at selected plasma densities. In order to have the best time resolution, dedicated experiments were made with all the sweeps at the maximum repetition rate of 35 μs (sweep duration 25 μs), corresponding to a total data acquisition window of 107.24 ms (limitation imposed by present system memory). New information could also be obtained at higher densities (up to $1.2\cdot10^{-20}$ m^{-3}) 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 and display also the spectral features due to plasma density perturbations, namely due to ELMs. Using spectrograms from consecutive sweeps it is possible to analyze the temporal evolution of the local spectra at selected probing frequencies (or 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 are intrinsic, the last one is triggered by pellet injection. An example of one of the spectrograms obtained between t=3.025515 s and t=3.025865 s (sweeps 730÷740) is depicted in fig. 2; in red it is marked the slice of the spectrogram at 59 GHz. The temporal evolution of the spectrogram slice at 59 GHz (n_e=$4.3{\cdot}10^{-19}$ m^{-3}) obtained from sweeps 730÷765, corresponding to the time interval t=3.025515÷3.026740 s, is re-presented in fig.3. The three vertical lines correspond, respectively, to sweep 736 (65 µs before the ELM), sweep 748 (355 µs after the ELM) and sweep 761 (810 µs after the ELM). 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 figure. The increase of the group delay starting at sweep 740

Fig. 1

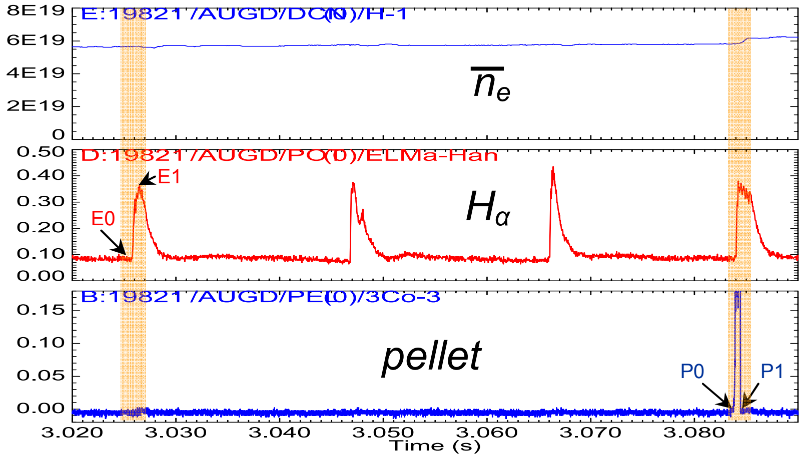


Fig. 2

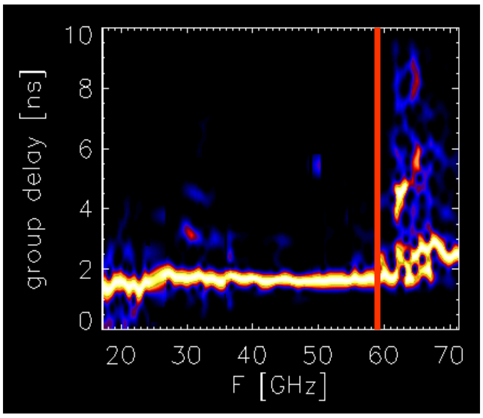
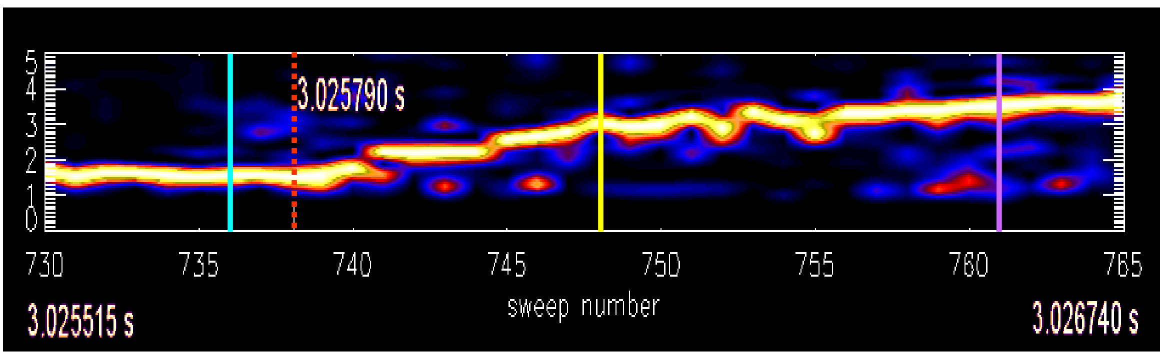


Fig. 3



(t=3.025865 s) indicates the inward movement of the density layer (away from the launching/receiving antenna) and therefore the density profile flattening caused by the ELM. It should be noted that, although important changes of the profile (group delay) occur and strong density perturbations are usually seen at the peak of the ELM, the selected plasma layer is not affected (spectral energy well concentrated around the group delay curve). To clarify the procedure, three of the thirty-six spectrograms utilized to perform the previous analysis are displayed in fig. 4 (they correspond to the sweeps indicated by the vertical lines in fig. 3). The slices at F=59 GHz are represented by the red vertical lines. The density profiles derived from these spectrograms (sweeps 736, 748 and 761) are shown in fig. 5, where the selected density layer is also indicated. It should be noted that only O-mode data was used to invert the profiles and the minimum probed density is $n_{e1} \cong 0.45 \cdot 10^{-19}$ m^{-3}. Below that density the profiles are initialized using a linearly approximation of the group delay curve and a fixed position r_0 for the first plasma layer. Although this procedure introduces some errors in the absolute position of density profile, the errors are more significant closer to n_{e1} and they decrease for higher densities.

Fig. 4

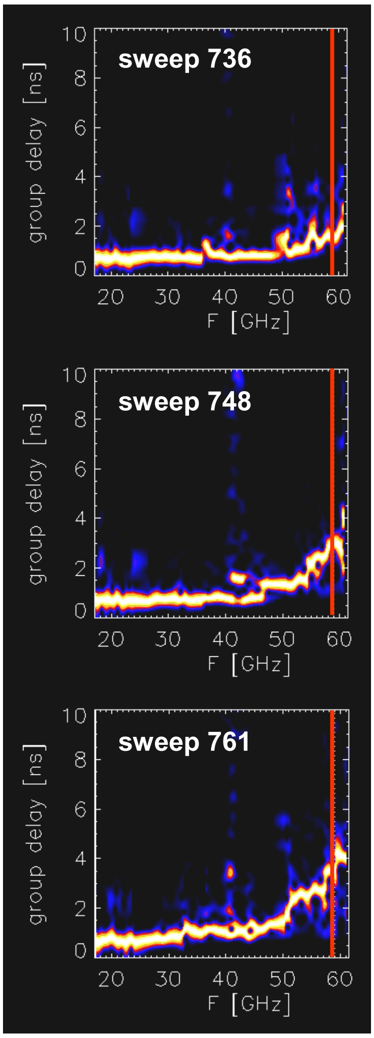
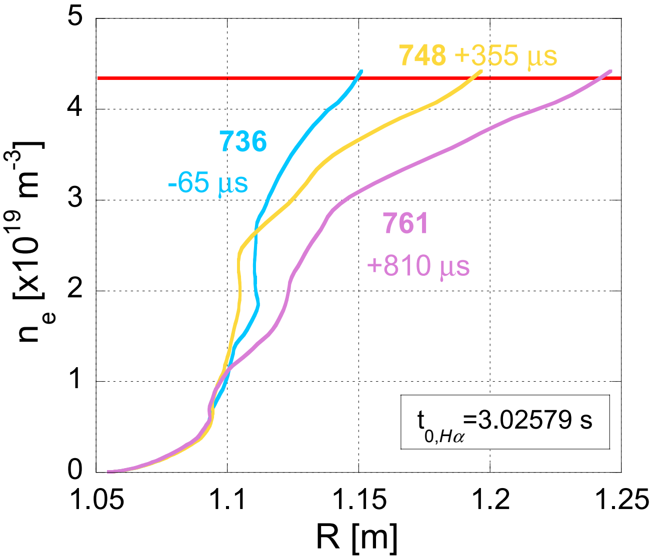


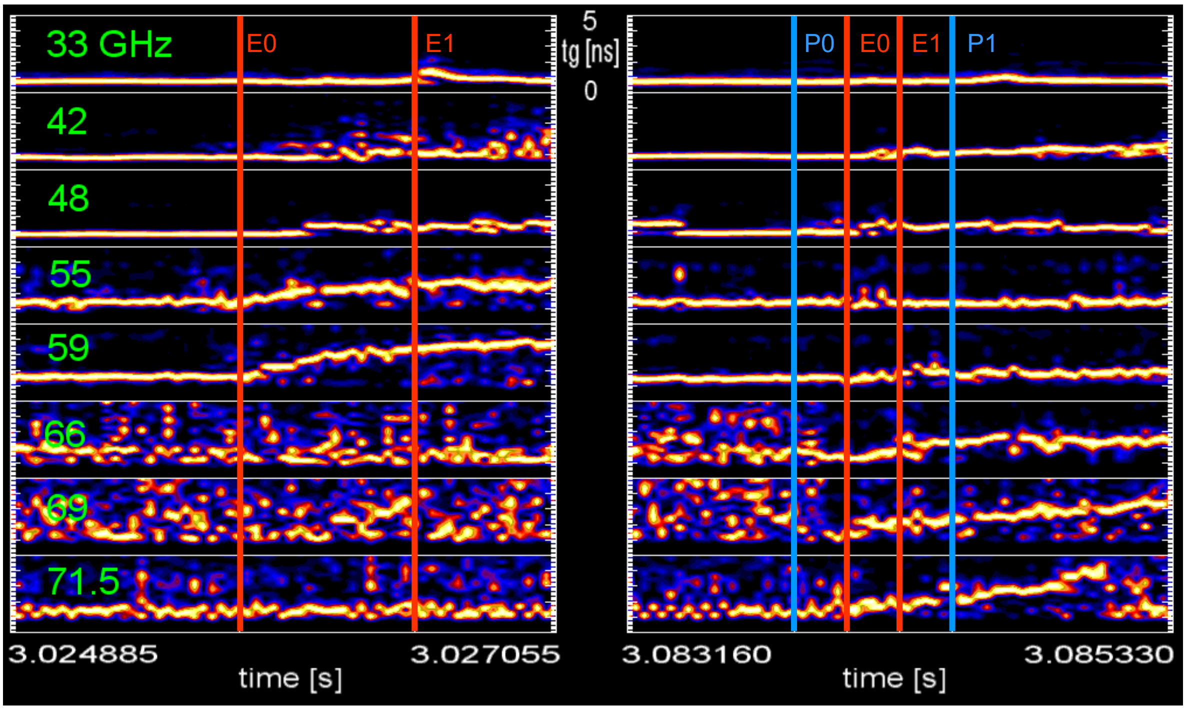
Fig. 5



Profile changes due to intrinsic and triggered ELMs

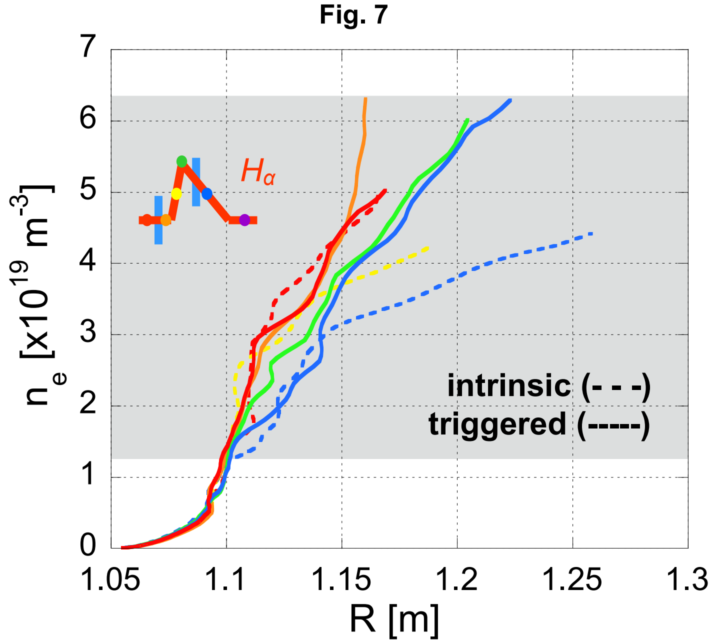
In the following we present the results concerning the first ELM (natural) and the fourth one (triggered) shown in fig. 1. With E0 and E1 we define, respectively, the beginning and the peak of the H_α signal. With P0 and P1 we indicate the beginning and the end of the pellet ablation in the plasma. We 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. 6). For the intrinsic ELM (left part of fig.6) 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 (n_e=5.4·10^{-19} m^{-3}), 69 (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).

Fig. 6



Moreover for these three frequencies 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 comes into operation. The GDSS plots also show how the density profile continues its flattening after the peaking of the H_α signal, E1.

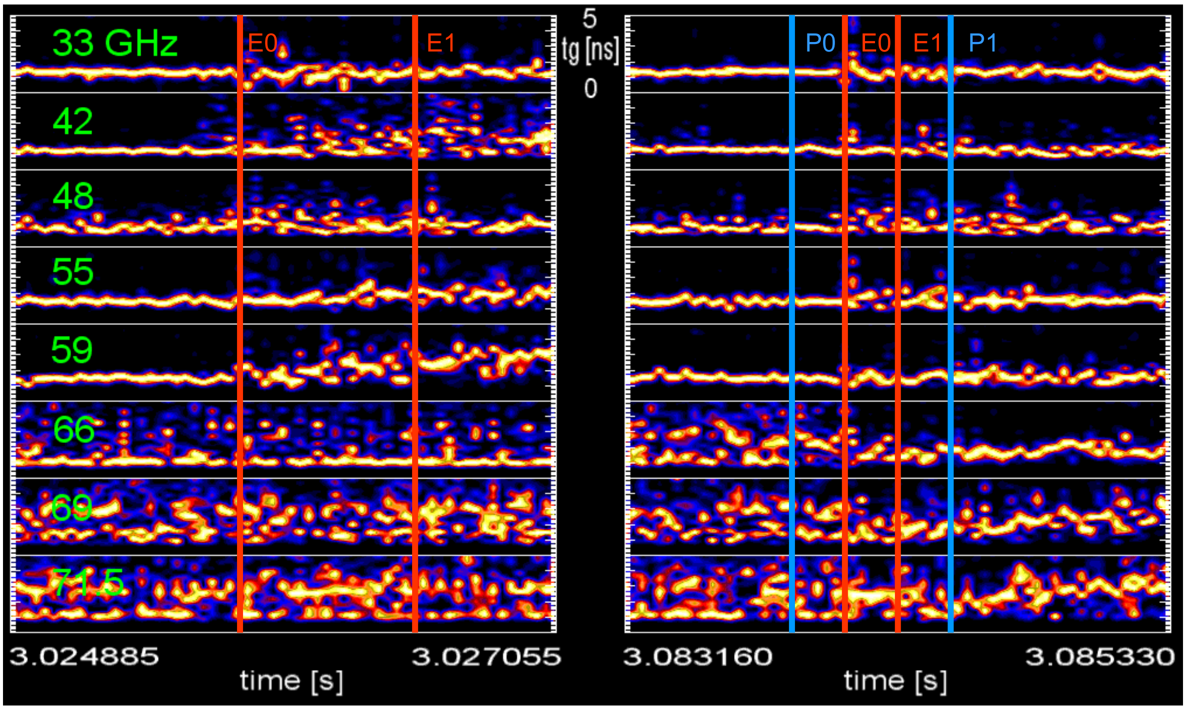
Fig. 7



In fig. 7 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. Concerning the LFS (fig. 8) the general behavior is similar to the HFS except that all plasma layers are more turbulent after the beginning of the ELMs.

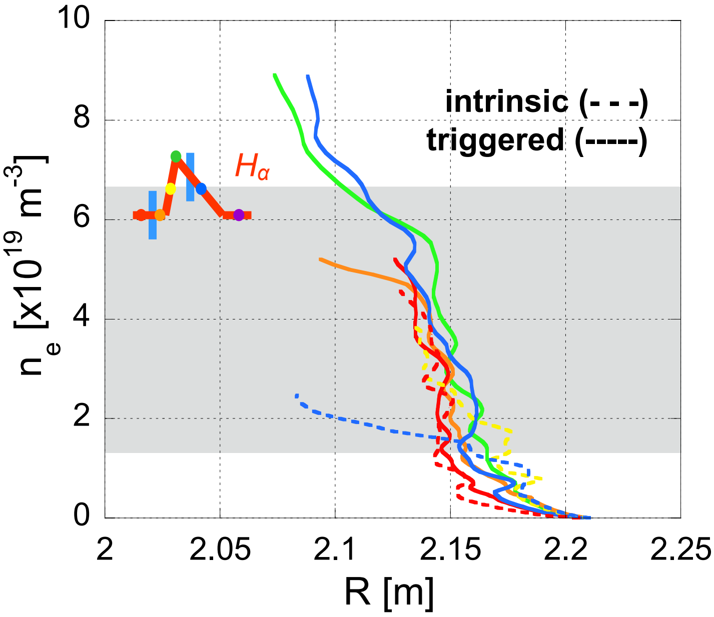
Moreover the density peaking due to the pellet injection is not immediate as it happens at the HFS. This is also confirmed from the LFS density profiles plotted in fig. 9.

Fig. 8



Conclusions

Fig. 9



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? For this more dedicated plasma experiments are foreseen. The analysis of the space time evolution of the plasma turbulence during the two types of ELMS is another relevant issue.

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