# ELMy Studies in ITER Relevant Regimes in ASDEX Upgrade Broadband FM-CW Reflectometry Techniques

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**Abstract.** We present a study performed in ASDEX Upgrade H mode regime based on results from the broadband FM-CW reflectometry diagnostic, equipped with the unique capability of measuring the plasma density profile both at the low and high field sides of the tokamak. The plasma edge dynamics due to fast events such as the Edge Localized Modes (ELMs) is analyzed displaying important characteristics of the ELMs and showing the high accuracy of the reflectometry diagnostic measurements.

**Keywords:** Fusion microwave reflectometry diagnostics. Physics of edge localized modes (ELMs).
**PACS:** 52.55.Fa Tokamaks, spherical tokamaks

## I. INTRODUCTION

Diagnostics using microwave reflectometry techniques are expected to play a major role in ITER. This is due mainly to its compatibility with the harsh burning plasma environment and the capability to perform a wide range of localized measurements, using limited access to the device. In ASDEX Upgrade (AUG) a FM-CW reflectometry diagnostic has been developed since 1991 and was successively improved with new hardware that extended its measuring capabilities. The main objectives of the system are to contribute to the AUG plasma physics studies and to demonstrate novel diagnostic techniques required for ITER, namely the possibility to control the plasma position and shape using reflectometry.

Here we present recent studies performed in AUG H mode regime which is the main ITER reference scenario. We describe the most important features of the FM-CW reflectometry diagnostic, namely its unique capability to measure the plasma density profile both at the low and high field sides (LFS/HFS) of the tokamak. High spatial and temporal resolution broadband measurements are presented that contribute to the investigation of edge localized modes (ELMs). These are edge perturbations with great impact in plasma transport and heat load in the divertor plates. The plasma edge dynamics due to ELMs is presented, namely the abrupt changes of the plasma density profile as well as the pedestal collapse. It is also analyzed the correlation of MHD activity due to ELMs with the observed profile changes.

## II. FM-CW reflectometry system on ASDEX Upgrade

The reflectometry system on ASDEX Upgrade operates in the frequency range [18 – 110 GHz] probing the plasma region [0.3-12.4 $\times 10^{19}$m$^{-3}$] with 13 channels [1,2]. The launching/emitting focused antennas are placed inside the machine both at the HFS and LFS. Four broadband channels propagating ordinary (O) mode waves are installed at the HFS to measure electron density profiles and plasma fluctuations in the density range 0.3 - 6.66$\times 10^{19}$m$^{-3}$. At the LFS the system has seven broadband channels for profile and fluctuation measurements, five operating in O-mode, covering the density range 0.3-12.4$\times 10^{19}$m$^{-3}$, and two extraordinary (X) mode channels in the frequency range 35 to 73 GHz (Q and V bands) to

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probe the outer edge density profile from zero density. Density profiles are measured simultaneously in 25μs with the operation of all broadband channels, both at HFS/LFS, with frequency swept operation. The spacing between profiles is variable, the minimum interval that can be set is 10μs. Presently, 3066 swept measurements can be performed at each side of the machine during each discharge; the number is limited by the memory of the data acquisition system.

Fluctuation measurements can be performed with all the broadband channels operating in fixed frequency plus the Q and V bands X mode channels dedicated to plasma fluctuation measurements. A very sensitive frequency hopping configuration was implemented in those two channels enabling to probe in each discharge fluctuations at several a-priori selected plasma density layers. The diagnostic is equipped with a very flexible dedicated control and data acquisition system.

## III. Pedestal evolution in the presence of ELMs

The H mode regime in tokamaks is characterized by the formation of a transport barrier at the edge close to the magnetic separatrix, resulting in a steep pressure gradient region, the so called pedestal. This narrow zone has a great influence in the plasma performance and is expected to play a critical role in future burning plasmas, like ITER. In figure 1 it is shown density profiles obtained with the FM-CW broadband reflectometry diagnostic (LFS/HFS) in AUG #1991 discharge.

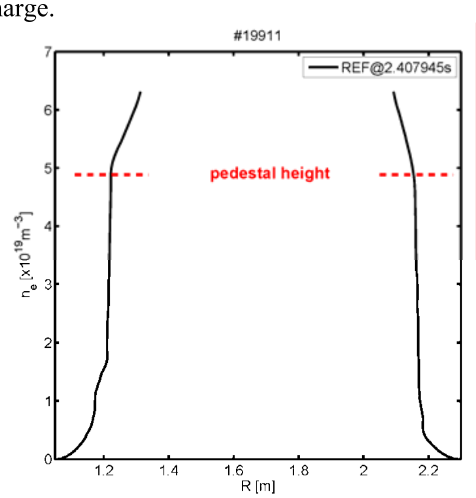


**Figure 1**

In this discharge the profiles were measured in 25μs, spaced by 10μs. As can be seen in figure 1, they display the typical features of improved confinement regimes, namely the steep edge region and a pronounced density shoulder at $n_e \sim 5x10^{19}m^{-3}$. The pedestal height (density at the plasma shoulder) is an important parameter because it indicates good (high value) or bad (low value) plasma performance. The value of the pedestal height is limited by the occurrence of magnetohydrodynamic (MHD) perturbations localized in the vicinity of the pedestal, the so called Edge Localized Modes (ELMs). These perturbations are repetitive and transport particles and energy across the plasma separatrix onto the divertor plates, decreasing the tokamak performance and creating a significant risk of divertor plate erosion, especially in future large machines. Understanding and controlling ELMs is therefore a main issue being currently investigated in many fusion devices, namely in AUG, with the main objective of attaining maximum performance with tolerable ELMs. In view of the importance of the pedestal height it is relevant to have this information available on a routine basis, as fast as possible, preferably between shots.

The density profile is derived from the group delay ($\tau_g$) due to the propagation and reflection of the probing microwaves over a large range of probing frequencies (F), using an Abel inversion. The $\tau_g$(F) curve is the basic information for density profile evaluation. In figure 2 are depicted two spectrograms of the plasma reflected signals obtained with a Short Fast Fourier Transform in AUG discharge #1991, one (a) between ELMs and the other (b) during an ELM. The abrupt increase of the group delay seen in (a) around $F_1$ = 65 GHz corresponds to density profile shoulder. This feature cannot be seen in (b) because the edge pedestal has collapsed due to the ELM occurrence.

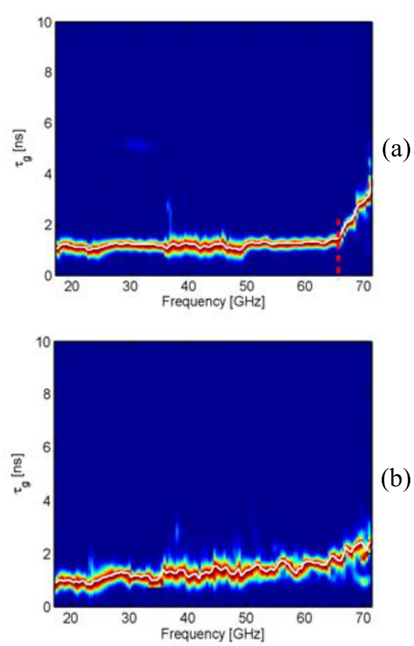


**Figure 2**

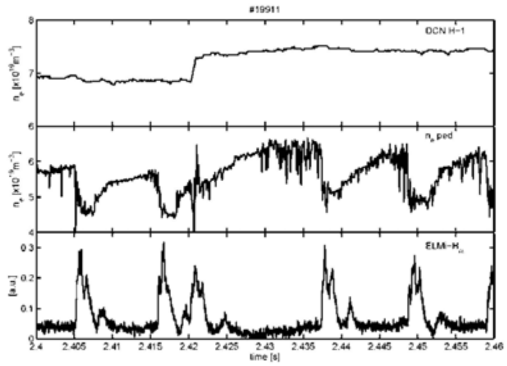


**Figure 3**

An algorithm has been developed to extract automatic $F_1$ [RSI 74 (2003) 1493]. This provides directly the density of the reflecting layer $n_{e1}$ (O mode probing) from,

$$F_1 \cong 9\sqrt{n_{e1}}$$

The result of such an automatic analysis of the pedestal height is presented in figure 3, for the time interval 2.40s – 2.46s in AUG discharge #1991, where four intrinsic type I ELMs and one pellet triggered ELM occurred. It is depicted, along with the evolution of the pedestal height, the time traces of the line average density obtained with the interferometer diagnostic, and the $H_\alpha$ radiation associated with the outward particles flux into the divertor plates. The injection of small size cryogenic Deuterium pellets from the HFS is one of the techniques used in AUG to establish pace making and mitigation of type I ELMs [3].

At t ~ 2.42s when a pellet was launched into the plasma from the HFS, a sudden increase of the plasma density occurred as observed by the abrupt jump of the average density measured by the interferometer diagnostic. That pellet triggered an ELM seen both from the abrupt increase of the $H_\alpha$ radiation and the sudden collapse of the pedestal measured by reflectometry. Three density profiles are shown in figure 4 illustrating the typical features of the density profile evolution during an ELM: (a) edge pedestal before the ELM; (b) pedestal collapse at the peak of the ELM, and abrupt re-appearance of the pedestal after the $H_\alpha$ signal drops to the values of the pre-ELM phase.
The results show that the profiles changes outward and inward around a turning narrow region (~ 1cm wider and located ~ 2.17m), in agreement with previous studies made in ASDEX Upgrade [4].

In figure 5 the magnetic perturbations associated with the ELMs measured with magnetic coils located at different toroidal, poloidal and radial positions are

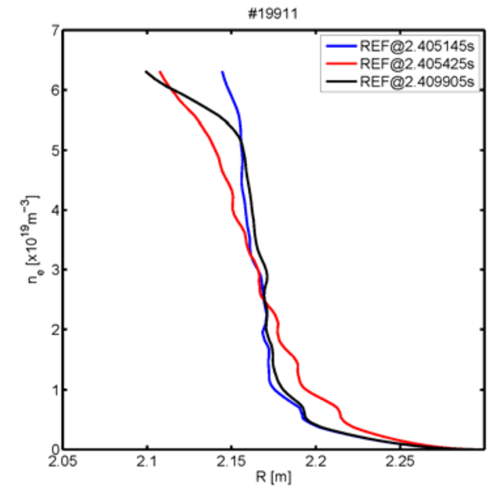


**Figure 4**

shown together with the Hα divertor radiation. For ELMs analyzed so far the onset of the abrupt profile changes coincides with the appearance of the MHD activity (marked by the grey bar) within about 100μs, which is consistent with the current physics understanding of the ELMs [5,6].

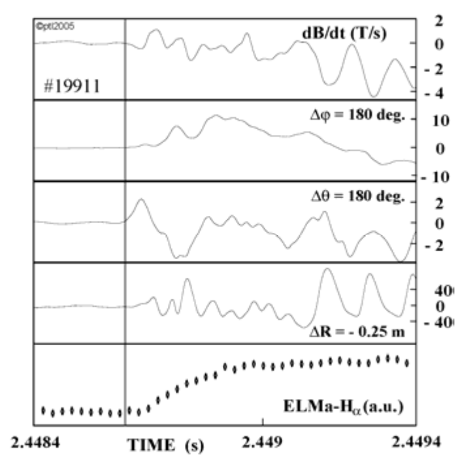


**Figure 5**

A further picture of edge profile dynamics under ELMs can be obtained from the detailed profile evolution at the LFS presented in figure 6. At the LFS the density time traces show clearly the two distinct regions seen previously in figure 4, separated by ~ 1cm around 2.17m. This should be the position of the last closed flux surface, separating the pedestal (< 2.17m) and the scrape of layer (SOL) (> 2.17m). The transport during the ELM (period of enhanced $D_\alpha$ light emission ~2-3ms) increases the SOL density during that period of time.

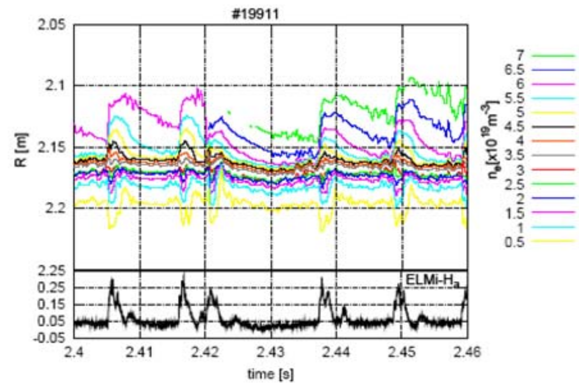


**Figure 6**

This increase is very sudden and happens within 100 μs timescale. The high SOL density is maintained during the ELM, but is back to pre-ELMs values immediately after the end of the period of enhanced $D_\alpha$ light emission. This corresponds to a low confinement expected for the SOL and the higher density can only be maintained by the strong influx of particles to the SOL from the core during the ELM. The density in the pedestal also collapses very quickly, within 100μs time scale, but recovers more slowly to the pre-ELM values taking ~ 10-20ms, which is approximately the ELM repetition time. This means that the confinement in the pedestal is good between ELMs, allowing the profiles to recover, but poor during the ELMs.
This is consistent with the expected picture of the density evolution in the pedestal and SOL regions during the ELM cycle.

## IV. Concluding remarks

It was shown in this work the high potentialities of the FM-CW broadband reflectometry system, providing contribute to the characterization of fast and important events such as the Edge Localized Modes. The dynamics of the density profile under the ELMs is being further investigated with the analysis of the density profile behavior of the HFS. Preliminary results concerning the HFS/LFS comparison seems to open new windows for the understanding of the physics underlying the ELM event, either intrinsic or triggered by pellets injected from the HFS.

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## REFERENCES

1. A. Silva, M. Manso et al, RSI 72 (2001) 307.
2. P.Varela, M. Manso et al, RSI 74 (2003) 1493.
3. P.T. Lang et al, NF 43(2003) 1110.
4. I. Nunes, M. Manso et al, NF 44 (2004) 883.
5. W. Suttrop et al, PPCF 42 (2000) A1
6. M. Becoulet et al, PPCF 45 (2003) A93.