Density Measurements with Broadband FM-CW Reflectometry in Advanced Scenarios on ASDEX Upgrade

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I. INTRODUCTION

The broadband reflectometry system on ASDEX Upgrade has been primarily designed to measure density profiles with the unique capability to make measurements simultaneously at the high and low fields sides (HFS/LFS). It is equipped with nine broadband channels that simultaneously probe the plasma to obtain the complete profile in 20 ?s. A total of 1440 profiles can be obtained during each discharge. All channels can also operate in fixed frequency for fluctuation measurements. Two fixed frequency channels were added to probe selected layers routinely during the complete discharge and in particular to monitor the L to H transition. The diagnostic is now very complex and a dedicated control and data acquisition system was developed that allows great flexibility in the selection of the measuring intervals and modes of operation. The diagnostic can be remotely operated from any computer connected to the internet through in-house built client-server software with multiplatform control/monitor clients. Great progress was made since the diagnostic was built in 1991 [1], due to the optimized design and hardware improvements, and the development of novel data analysis and software tools for automatic profile evaluation [2]. Here we present recent measurements performed in different plasma regimes, namely in advanced plasma scenarios, such as improved H-mode plasmas and H-mode discharges with inboard launch pellet fuelling. The effect of plasma turbulence on profile measurements is analysed and it is shown that profile perturbations contain useful information about the plasma underlying phenomena. Finally we give examples showing the ability of the reflectometry broadband diagnostic on ASDEX Upgrade to track plasma movements.

II. DENSITY PROFILE AND FLUCTUATION MEASUREMENTS IN IMPROVED H-MODES

The improved H-mode regime in ASDEX Upgrade is generally obtained through NBI pre-heating in the current ramp up phase. The power is increased at the end of that phase causing a transition into the H-mode, and a stationary phase is obtained. Previous studies showed that the density profile peaks at lower density and exhibits a steep increase of peaking correlated with the flattening of the electron temperature. The ion stored energy increases significantly due to the density peaking while for the electrons the increase is only small [3]. Density profiles obtained with reflectometry in improved H mode regime in ASDEX Upgrade shot # 13037 are depicted in Fig.1. In this discharge neutral beam was increased from 2.5 MW to 5 MW at t = 1.040 s and the stationary phase starts at t ~1.4s. An L to dithering phase (with type III ELMs) occurs at t = 1.1 s. The further improvement of the H barrier occurs at t = 1.17 s and is stronger at t = 1.21s. An ion ITB seems to develop in the time interval 1.1s to 1.25s and collapses afterwards, back to the usual H-mode with type I ELMs (see Fig. 1a). In Fig.1 b) and c) are shown two sets of 8 profiles from O-mode reflectometry with 20 ?s temporal resolution, each set burst corresponding to 8 consecutive sweeps. The deviation between profiles in each burst is due to the plasma turbulence. These are less pronounced at t ~ 1.24s, when the level of turbulence is lower following the formation of the H barrier. Average profiles d) can be obtained from each burst, as it is depicted in Fig. 1 d) displaying the evolution of the average profiles (240 ?s) between 0.9s and 2.9s, In Fig.2 it is represented the evolution of both n_e and $?n_e/?r$ for several radial locations derived from the average profiles at radial positions, at the edge, both at HFS (R=1.20m, R=1.30m) and LFS (R=2.13m, R=2.00m), n_e and $?n_e/?r$ follow the gross evolution of both the central Ti and the stored energy, indicating

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the changes in confinement. The evolution of the density gradient can be better seen at the HFS due to the lower level of plasma turbulence and more spaced flux surfaces. The gradient at the separatrix starts to peak for t ~1.1s and decreases for t ~ 2.5s, when the H to L mode back transition occurs and the confinement degrades. Interesting to note is the peaking of the profile at the inner radius between 1.1s and 1.2s (increase of both n_e and ?n_e/?r) in the time interval where ITB develops.

A complementary analysis of the behaviour of turbu-

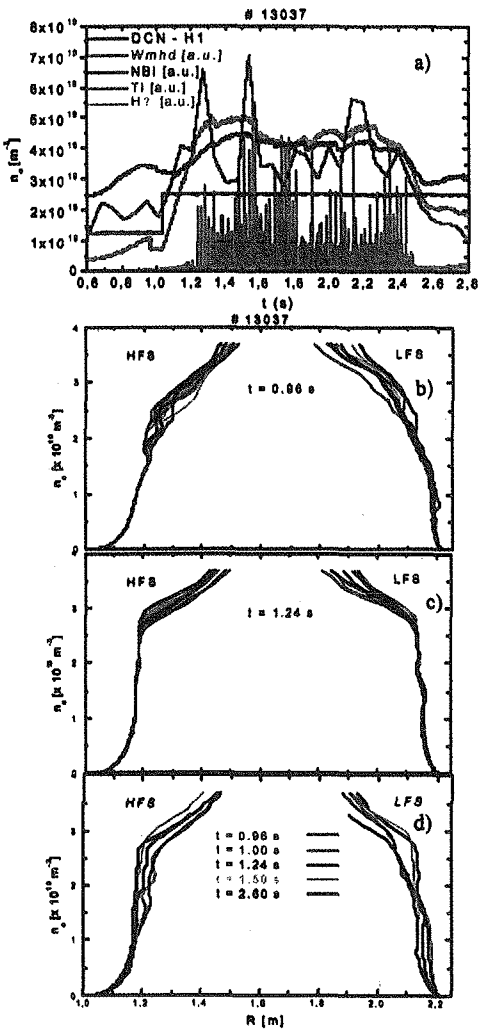

Fig. 1

lence can be obtained from fixed frequency operation. Fig.3a shows the contour plot of the power spectra reflected from a density layer n_e ~ 3? 10^{19} m^{-3}, in the time interval 0.6 - 2.8s. With the NBI increase at t=1.04s, the spectra of turbulence begins to change showing a gradual shift in the power to higher frequencies, which indicates the increase of the plasma rotation. A reduction of the turbulence in the range up to ~ 80 kHz is observed after 1.1s, corresponding to the L to dithering H-mode transition at the edge as

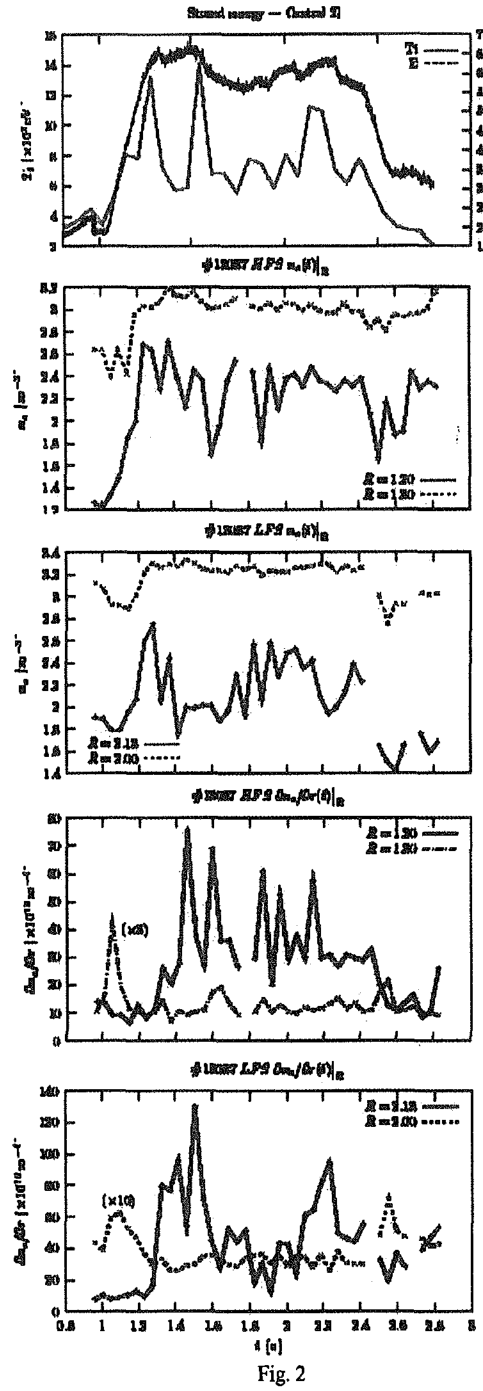

Fig. 2

well as to the formation of an ion ITB. At t = 1.21 s an abrupt suppression of the high frequency turbulence occurs (see the integrated power spectrum above 80 kHz in Fig.3b), indicating a strong development in the

H-mode barrier. The background fluctuations appearing after 1.25s correspond to type I ELMs and to the destabilization of MHD modes (seen as traces in Fig.3a), leading to the locking of a NTM at t ~ 2.5s.

Above it was shown that the profile perturbations are

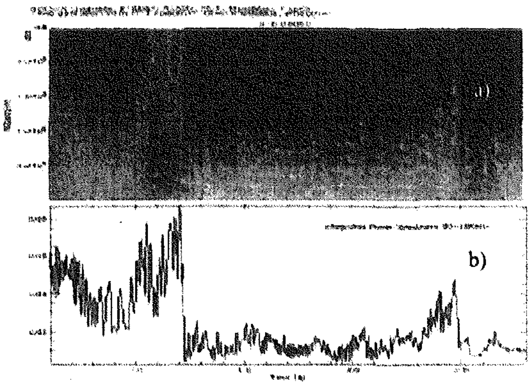

Fig. 3

strongly correlated with plasma turbulence. Another example is given in the following referring to improved H-mode discharge #13429. In Fig.4 the mapping of the level of profile perturbations in time and density (estimated with a P parameter), is shown during the ELMy H mode phase. P is defined as P = 1-?, where ? is the ratio between energy in the reflected signals that can be attributed to distance information and the total energy in the reflected waves. As the energy is concentrated in a narrow beat frequency inter-

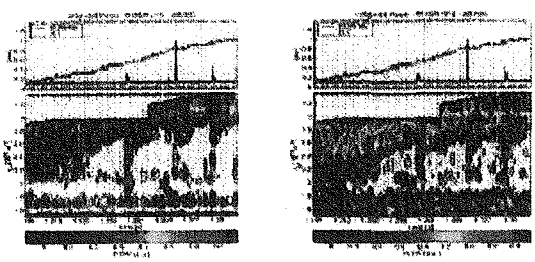

Fig. 4

val when the level of turbulence is very low, and is displaced to other beat frequencies (proportional to the group delay of probing microwaves) locations when turbulence level is high [2], the P parameter ranges from almost zero in the case of low turbulence (? ? 1), to one for strong turbulence. In Fig 4 it can be seen that the profile perturbations are low at the edge where turbulence is low due to the H mode barrier. The evolution of the edge pedestal (density) can be visualized from the evolution of the upper boundary line of the zone with reduced fluctuations. It increases following the development of the edge barrier and associated increase of the average density. After each ELM the fluctuations invade the edge region and are also seen close and inside the separatrix, corresponding to the abrupt flattening of the density profile at the onset of each ELM and slower recovery afterwards, the mapping of the profile perturbations shows, therefore, the space time evolution of ELMs. Moreover it maps the evolution of the density at the edge pedestal, which is a key indicator of confinement improvement.

III. DENSITY PROFILES DURING INBOARD PELLET LAUNCH EXPERIMENTS

A difficult situation for reflectometry is during inboard pellet experiments due to the strong plasma movements and strong ELM activity, including giant ELMs [4]. A selection of individual profiles depicted in Fig.5 shows that some profiles can be measured without significant deformations in these unfavorable

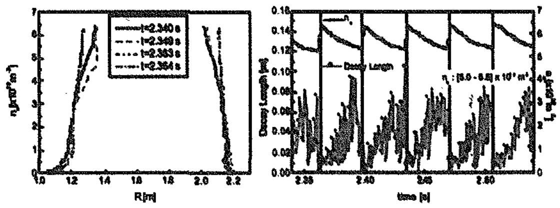

Fig. 5

circumstances. The evolution of the decay length at the plasma region n_e:5-6.5 x 10^{20} m^{-3}, reveal the peaking of the profile (decrease of decay length), after the injection of each pellet (dashed lines) followed by a flattening of the profile (increase of decay length) and a recovery before the next pellet. From the spread of the decay length points derived from individual profiles, (without any averaging procedure), it is evident that plasma turbulence induced by the pellets cause significant profile deformations. However, these do not prevent obtaining the evolution of the decay length and to evaluate the sustainment time of the peaking of the profile after each pellet. From these profile measurements a study was performed for different pellet velocities suggesting that for increased pellet injection velocity the sustainment time increases at the HFS, which may indicate an improvement of the confinement [5].

IV. TRACKING OF PLASMA MOVEMENTS

Reflectometry has been proposed as a new approach to plasma position and shape control for long pulse operation on next step machines like ITER, when magnetic systems may accumulate significant errors. This is a new application of reflectometry that should be demonstrated in present machines. The FM-CW reflectometry system on ASDEX Upgrade has unique possibilities to detect plasma movements, because it probes the plasma simultaneously at the high and low

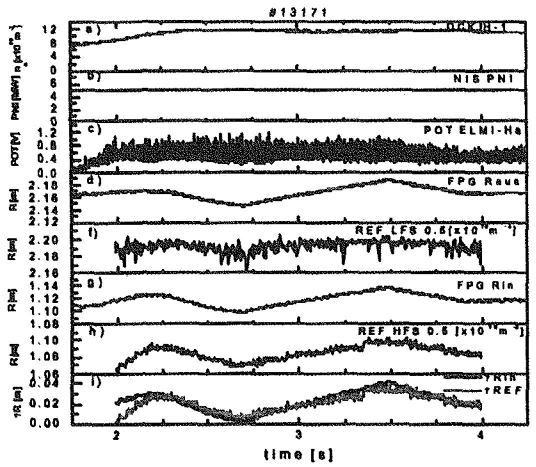

Fig. 6

field sides with identical O-mode reflectometers (not sensitive to the B-field). First experiments were performed in a discharge where the plasma was scanned radially between t = 2.2s and t = 3.8s. From Fig.6 it can be seen that the temporal evolution of the radial position of density layers with $n_e = 0.5 \times 10^{19}$ m^{-3}, at the HFS/LFS, is in good agreement with the plasma position (Rin and Raus), derived from the magnetic measurements. Due to the higher level of plasma turbulence at the LFS (ELMy H regime), the plasma movements are more clearly detected at the HFS. It should be noted that a deviation is observed for t < 2.25s (before the radial plasma position is scanned), due to density build up, as seen in the evolution of the average density (first trace at the top of Fig. 6). The

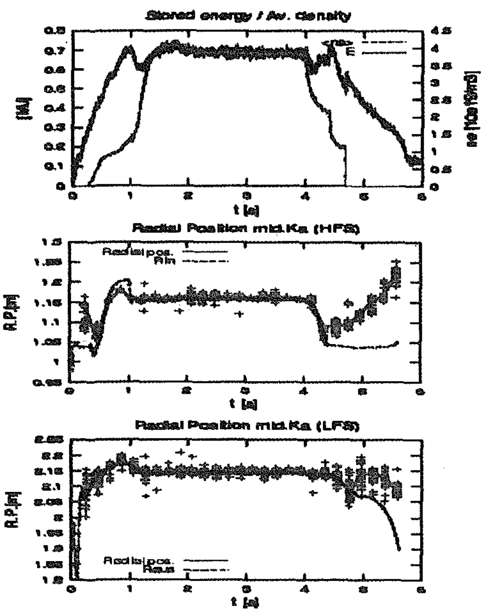

Fig. 7

next example is given in Fig.7, showing the radial movements of density layers $n_e = 0.5 \times 10^{19}$ m^{-3}, located at the HFS and LFS. Reflectometry is able to track the plasma position during both the start-up and in the stationary phases of the discharge. During the shut down phase, for t > 4.1s, reflectometry follows the movements away from the antennas of the selected density layer at both sides, indicating an asymmetric collapse of the plasma.

V. CONCLUDING REMARKS

We showed that the FM-CW microwave reflectometry on ASDEX Upgrade provides reliable and automatic density profiles in advanced plasma scenarios even in the presence of strong plasma turbulence. It was shown that profile perturbations are intrinsic to the plasma behaviour and can provide important information about the plasma phenomena. Broadband profile measurements (probing the plasma in short discrete time windows and large spatial windows) and fixed frequency probing (large time windows and narrow spatial windows) should be used in a complementary way to study plasma turbulence. HFS/LFS measurements are an important tool to the plasma diagnostic. It was shown that FM-CW reflectometry has the ability to track plasma movements, which is the first experimental demonstration where will be possible to use reflectometry for control purposes, as it is proposed for ITER. Further work is foreseen using the enhanced capabilities of the diagnostic that is presently being upgrade to improve the core measurements and to the number of profiles per discharge to 4320.

ACKNOWLEDGMENTS

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