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Advances in the density profile evaluation from broadband reflectometry on ASDEX Upgrade

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The high temporal and spatial resolutions provided by broadband microwave reflectometry make it an attractive diagnostic technique to measure the density profile in fusion plasmas. However, great problems have been encountered due to the plasma turbulence that difficult, and sometimes prevent, the routine evaluation of density profiles. Advanced broadband systems employ ultra-fast sweeping in an attempt to perform the profile measurement in a time window smaller than the temporal scale of the main plasma fluctuations but this is not sufficient. Indeed, abrupt plasma movements and/or spatial turbulence always affect the reflectometry signals, as shown by numerical studies (with both one- and two-dimensional codes), for the case of ultra-fast sweeping and pulse radar systems. For this reason not only the system performance is important but the software tools also play a crucial role for reflectometry to become a standard density profile diagnostic. Here we present the recent advances towards automatic evaluation of density profiles from broadband reflectometry on ASDEX Upgrade. For regimes with moderate levels of plasma turbulence, density profiles are obtained from single reflectometry samples (temporal resolution of 20μs), and for higher turbulence levels average profiles are obtained from bursts of ultra-fast (20μs), closely spaced (10μs) sweeps. This method improved the accuracy and reliability of density profiles, which can now be obtained automatically from the edge to the bulk plasma – using reflectometry alone – in most plasma regimes of ASDEX Upgrade. New data processing capability has been implemented that allows the profiles to be available to the end-users 10–12 minutes after each discharge. These developments were possible due to the flexibility and high performance of the control and data acquisition systems and to the large number of measurements that can be performed with the diagnostic during each discharge (720 profiles both on the low- and high-field sides).

I. INTRODUCTION

Broadband microwave reflectometry has great potentialities to measure the electron density profile in magnetic confinement fusion devices, mainly due to the high temporal and spatial resolutions it provides, and to the relatively reduced machine access it requires. However, the automatic routine evaluation of density profiles has been hard to achieve due to the effects of plasma turbulence in the reflectometry signals. Advanced broadband reflectometry diagnostics attempt to reduce the effect of plasma turbulence by performing the profile measurement in a time window smaller than the temporal scale of typical plasma fluctuations.

The results obtained in ASDEX Upgrade with broadband ultra-fast sweeping (20μs) indicate that the perturbations exhibit by the density profile can be correlated with plasma turbulence, as well as with fast and localized movements of the density layers, such as those occurring during edge localized modes (ELMs). Numerical simulations performed with a two-dimensional full-wave code[1] that includes the relevant features of the ASDEX Upgrade broadband reflectometer, have confirmed these effects. Although some effects may be attributed in part to the finite probing time, simulation studies performed with a one-dimensional code[2] show that even in the case of the quasi-instantaneous pulse radar technique, the spatial turbulence, which cannot be avoided, still induces significant errors in the profile evaluation. This shows that not only the system performance is important but also software tools for group delay evaluation play a crucial role for reflectometry to become a standard density profile diagnostic.

Our approach in designing the ASDEX Upgrade broadband reflectometer[3,4] was to implement a flexible and high performance system complemented by advanced data analysis tools capable of estimating the group delay versus probing frequency curves in the presence of plasma turbulence. Here we present the recent advances in the data processing system that en-

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abled the automatic routine evaluation of density profiles, and their availability to the users 10–12 minutes after each discharge.

The remainder of the paper is organized has follows. In Sec. II, the improvements to the profile evaluation are presented. Section III describes the automatic routine evaluation of density profiles implemented on the ASDEX Upgrade reflectometer. Finally, Sec. IV summarizes and gives some hints concerning future work.

II. IMPROVED PROFILE MEASUREMENTS

The broadband reflectometer in the ASDEX Upgrade tokamak was specifically designed to meet several measurement requirements, in particular those of density profile measurements. The system features ultra-fast sweeping and has the unique capability of probing from both magnetic field sides simultaneously. Profile measurements can be performed in several modes: (i) equally spaced covering the complete discharge, (ii) in burst-mode, with bursts of closely spaced sweeps with a larger interval between the bursts, and (iii) in a mixed mode, where parts of the discharge are covered with single measurements and others with bursts. In burst-mode, the number of sweeps per burst, the time interval between sweeps, and the spacing between bursts can be made different along the discharge. This is especially useful when it is required to cover parts of a discharge in detail, as is the case of L-H transitions.

The accuracy of profile measurements on ASDEX Upgrade depends heavily on the data processing tools. The most important piece of the data processing system is the group delay estimation code, which is based on the best-path algorithm.[5] This algorithm uses the spectrogram of the reflected signals, which shows how the reflected energy is distributed in the time-frequency domain. Fig. 1 shows two examples of spectrograms obtained during an ASDEX Upgrade H-mode discharge. The spectrogram in Fig. 1(a) corresponds to a profile measured just before (120μs) an ELM while Fig. 1(b) depicts the spectrogram corresponding to a profile measured at the onset of the same ELM as shown in the H_α trace in Fig. 1(c), where the red and blue lines mark the measurement times of the profiles corresponding to Fig. 1(a) and 1(b), respectively. The group delay curve shown in Fig. 1(a) (white line) is a good estimate due to the relative low level of turbulence when compared with the situation depicted in Fig. 1(b).

The results obtained so far in ASDEX Upgrade show that the signal-to-noise ratio (S/N) of the reflectometry signals plays an important role in the automatic evaluation of the profiles. If the S/N is high the inversion of the profile from single sweep data presents no problems, which is normally the case in plasma regimes with low levels of plasma turbulence such as in H-mode plasmas. When the level of turbulence increases the S/N ratio may become very low (in one or more probing frequency ranges) preventing the accurate inversion of the density profile. The solution to this problem usually consists in averaging over several consecutive sweeps to improve accuracy. However, care must be taken to ensure that samples are correlated so that the obtained average profile is meaningful.

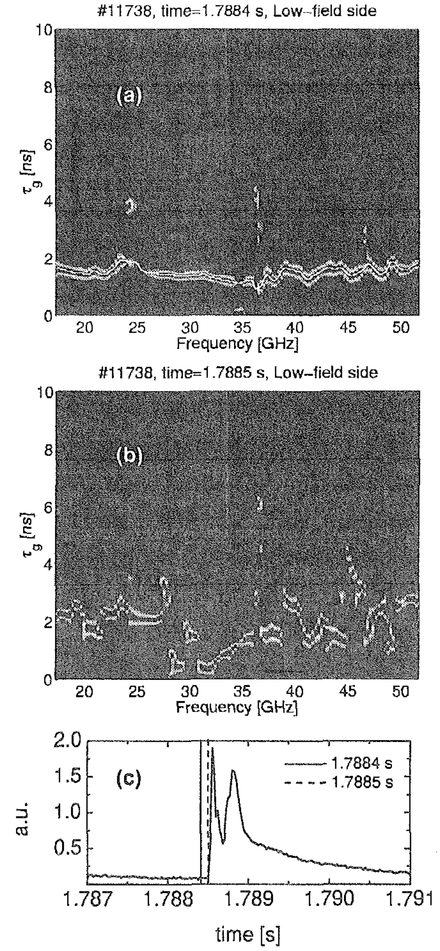

FIG. 1. Examples of spectrograms obtained from 20μs sweeps: (a) 120μs before a fast ELM occurs, (b) at the onset of the ELM, and (c) H_α emission. The vertical lines on (c) mark the measurement times of the profiles corresponding to (a) and (b), respectively.

In ASDEX Upgrade we take advantage of both the ultra-fast sweeping capability of the diagnostic and of the large number of measurements that can be performed in a single discharge to operate in burst-mode. The typical setup is to have bursts of eight closely spaced (10μs) ultra-fast sweeps (20μs) to obtain an average profile with a temporal resolution of 230μs. The interval between bursts can be tailored according to the physics needs.

The average profile cannot be obtained from simple averaging over the ensemble of group delays, as it is too sensitive to strong perturbations in the individual samples. To avoid this problem a burst-mode data analysis method has been developed. The method considers all the information in the individual spectrograms to compute the burst profile. The computed burst-mode spectrogram retains the features common to the different sweeps while strongly reducing the perturbations of the individual group delays, therefore giving a more accurate and reliable burst profile.[6]

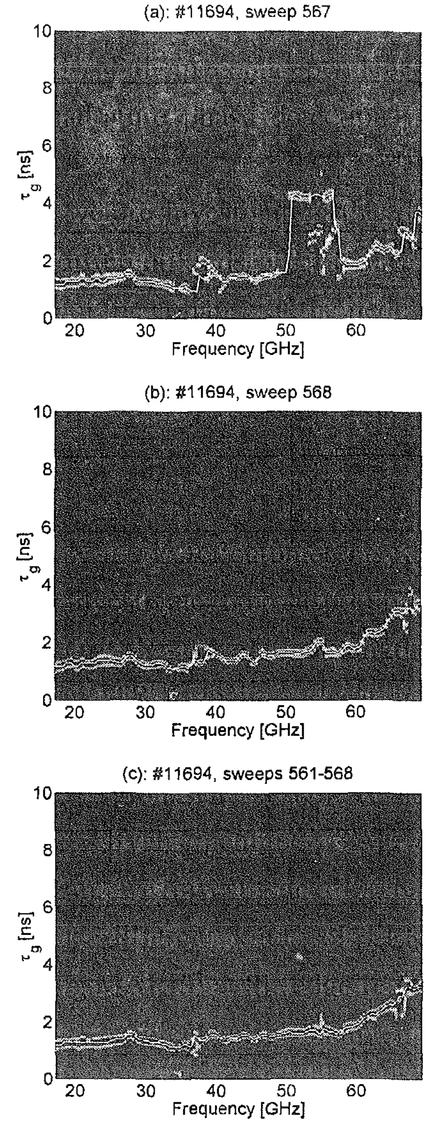

FIG. 2. Example of the application of the burst-mode data analysis method to eight (561–568) consecutive sweeps (20μs sweep time separated by 10μs) measured during an H-mode ASDEX Upgrade discharge: (a) and (b) spectrograms of two individual sweeps, 567 and 568, respectively; (c) burst spectrogram obtained with the burst-mode data analysis.

An example of the application of this analysis technique is shown in Fig. 2, which refers to the analysis of eight (561–568) consecutive sweeps spaced by 10μs. Figures 2(a) and 2(b) show two spectrograms corresponding to two individual sweeps (20μs) within the burst, where the group delays (white lines) obtained using the best-path algorithm are also displayed. In sweep 567 a strong perturbation is observed in the time-frequency distribution (and in the group delay) in the frequency range 50–58, where as in the next sweep the perturbation has disappeared. Smaller perturbations appear at different frequency locations in some of the other six spectrograms of the burst. The burst mode spectrogram (Fig. 2(c)) and the density profiles corresponding to the single and burst-mode analysis (Fig. 3) demonstrate the advantage of this multiple sweep analysis to obtain more accurate profiles. In fact, the group delay curve obtained using the burst-mode analysis is not affected by the strong deformations present in sweep 567, as it would happen if simple average were used.

Another advantage of burst-mode measurements is to improve accuracy and reliability while keeping a high temporal resolution and maintaining the profile measurement rate.

III. AUTOMATED ROUTINE EVALUATION

A crucial step for reflectometry to become a standard diagnostic is profile availability. Due to the large amounts of data acquired during a single discharge interactive data processing is not an option. The availability of the density profiles in a between-shots basis requires automatic evaluation.

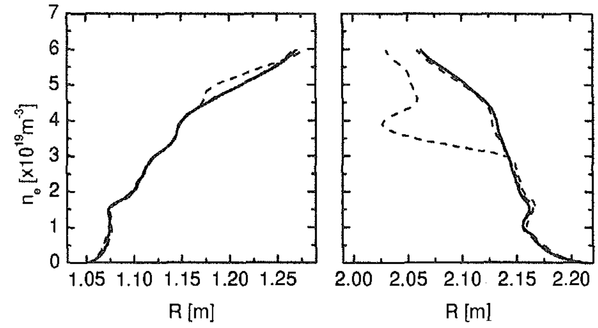

FIG. 3. Density profiles from the high-field side (left) and low-field side (right) inverted using single sweep data (dashed lines) and with the burst-mode analysis (solid lines) corresponding to the situation illustrated in Fig.2.

In ASDEX Upgrade, storage of diagnostic data is organized in shotfiles. Level-0 shotfiles contain the raw data and level-1 and subsequent shotfiles contain processed data. In the case of the reflectometry diagnostic level-1 shotfiles contain the density profiles obtained with single sweep data analysis. Level-2 shotfiles contain smoothed versions of the level-1 profiles together with median profiles, and burst-mode profiles obtained using burst-mode data analysis.

Reflectometry profiles are most useful if they are available to the end-users between discharges. With this in mind a fully automatic density profile evaluation procedure was implemented that enables to provide level-1 and level-2 profiles 10–12 minutes after each discharge. A monitoring process is launched in the background that waits for a new shot to be acquired. As soon as data is available for that shot the background process starts the level-1 and level-2 evaluation codes and waits for the next shot. The level-2 application stays idle waiting for available level-1 data. When this happens level-2 shotfile creation starts. To make the profiles available as quickly as possible the level-1 shotfile application subdivides itself into a number of smaller processes (typically eight) – a sub set of the acquired data is given to each sub process for evaluation. At the end, the results from the several sub processes are collected and the level-1 shotfile is created.

The automation of the profile evaluation faced three main problems: (1) the adjustment of the filters used to remove low amplitude modulations and high frequency noise, (2) profile initialization, and (3) the detection of the probing frequency above which the system is no longer in reflection.

As long as the S/N is high enough, the solution we adopted for the first problem was to keep the filters sufficiently open to accommodate a wide range of beat frequencies in all microwave channels. Concerning initialization, data from the X-mode channels can be used whenever available. Otherwise linear dependency on the probing frequency is assumed for the unmeasured part of the group delay. Work is going on to solve the problem of detecting the last reflecting probing frequency. An algorithm that estimates similarities between the plasma reflected signals and measurements performed while the reflectometer is in transmission mode is being developed, and it should be tested for accuracy and robustness during the next ASDEX Upgrade campaign.

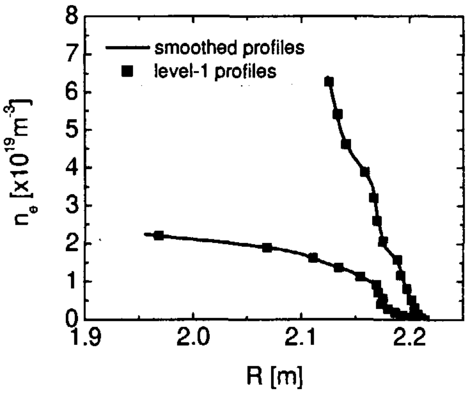

FIG. 4. Application of the smoothing algorithm to two level-1 profiles. For clarity only some points (squares) of the level-1 profiles are plotted.

Another problem is finding a suitable smoothing/fitting procedure to the group delay data that enables to obtain monotonic density profiles while retaining the essential structure of the measured profiles. An initial approach based on an iterative cubic spline approximation was implemented. The smoothing is done directly on the measured group delays (either from continuous or burst-mode measurements) to avoid the integration errors present in the inverted profiles. The iteration stops as soon as the smoothed profile is monotonic. Only profiles that become monotonic without over smoothing and with low mean-square errors are stored in level-2 shotfiles. The measured and smoothed profiles for low- and high-density examples are shown in Fig. 4. For clarity only some points of the level-1 profiles are plotted.

IV. SUMMARY AND FUTURE WORK

This paper describes the advances in the data processing system of the ASDEX Upgrade broadband reflectometer that improved the accuracy and reliability of the density profiles, which can now be obtained from the edge to the bulk plasma from reflectometry alone. The new data processing capabilities allow the density profiles to be available to the end-users 10–12 minutes after each discharge, which is a very important step for reflectometry to become a standard diagnostic. The high flexibility and performance of the reflectometer namely its capability to measure a large number of profiles during each discharge enabled the use of burst mode measurements, which are crucial to obtain accurate density profiles in the presence of high levels of plasma turbulence.

Currently, the acquisition system is based on in-house built, four channel, VME boards with 250 MHz maximum sampling rate and 720KB of memory per channel. With this setup 720 profiles can be measured on each magnetic field side, per discharge. To extend the measurement capability of the diagnostic the acquisition system is presently being upgraded to 3MB per channel, which will allow measuring 3000 profiles, per side, per shot. This will make it possible to operate in burst mode during the complete discharge.

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