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# Automatic evaluation of plasma density profiles from microwave reflectometry on ASDEX upgrade based on the time-frequency distribution of the reflected signals

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A new data analysis technique has been developed for the evaluation of the density profiles from broadband reflectometry in the presence of plasma turbulence. The method is based on the spectrogram of the reflected signals and uses the complete information of the beat frequency spectrum. The application of the Floyd best path algorithm, that takes into account the history of the beat frequency curve, enables us to extract the slow component due to the plasma profile. The statistics of the group delay data points is also considered to validate (or reject) data with great confidence. The results obtained in a wide range of plasma regimes show that accurate and detailed profiles can be measured automatically. One and two dimensional moving averaging over consecutive sweeps is also available to reduce the variance of the inverted profile while retaining a good temporal resolution. © *1999 American Institute of Physics.* [S0034-6748(99)71001-4]

## I. INTRODUCTION

The relevant information needed for density profile evaluation from broadband reflectometry is the group delay $\tau_g$ of the probing waves, due to the propagation and reflection at the cutoff layer. The group delay is related to the beat frequency $f_b$ of the detected signals by $\tau_g(F) = 2\pi^{-1} f_b(F)$, where $F$ is the incident frequency swept over a short time interval (10–100 $\mu$s).

Due to the propagation close to the cutoff reflectometry is very sensitive to fluctuations and as a result the energy of the reflected signals is scattered over several frequencies. In extreme cases the slow $f_b$ component due to the average profile may vanish for some range of $F$ preventing the detection of the corresponding $f_b$ values.

Temporal and spectral analysis have been used to evaluate the profile under the presence of plasma fluctuations. In the first case narrow filtering is employed to eliminate the spurious frequency components caused by turbulence. The filter should be well adapted to the slow varying $f_b$ component (which is not an easy task due to the scattering of energy by the plasma fluctuations) because $f_b$ has the tendency to follow the filter central frequency and deviates from the correct $f_b$. It should be underlined that small deviations of $f_b$ over small ranges of $F$ can cause significant deviations of the profile because the errors accumulate in the profile inversion.

Standard spectral techniques use a sliding fast Fourier transform (FFT) to obtain the time resolved frequency spectrum and take the main peak frequency as the estimate of $f_b$. Experimental data shows that under strong fluctuations or fast displacements of the reflecting layer [e.g., due to edge localized modes (ELMs) or magnetic modes] the main peaks do not corresponds to the average profile. To avoid this, *a priori* narrow filtering is also used and therefore this type of analysis suffers from the same type of errors encountered in the temporal analysis.

Recently, a method has been developed[1] based on the spectrogram of the reflected signals. The technique uses the first moment of the spectrogram[2] to estimate the average beat frequency curve. More recently, another technique based on the Wigner–Ville distribution (WVD)[2] was proposed.[3] The results show that the WVD is specially suited for tracking fast frequency features of the reflected signals. But, as the beat frequency corresponding to the average profile is slowly varying with $F$, the spectrogram based techniques are suitable and more attractive due to their simplicity when compared to the computational complexity of the WVD.

However, the evaluation of the profile from the first moment of the spectrogram can cause significant distortions due to the assymetries of the $f_b$ spectrum around the relevant $f_b$ component. To overcome this problem we further develop the spectrogram technique. The new method is based on the Floyd best path algorithm[4] and uses the complete information about the local $f_b$ spectrum. As reflectometry produces a large amount of data and the reflected signals can be strongly disturbed by fluctuations for very short time intervals (100 $\mu$s or less), the data processing also includes algorithms which validate or reject the $\tau_g$ curve, thus improving the profile accuracy. With the above features the new data analysis is specially suited for automatic profile evaluation.

The remainder of this article is organized as follows. Section II focuses on the fundamentals of the algorithms. In Sec. III experimental results are presented and the application of the method is discussed. Finally, in Sec. IV we draw some conclusions about the potential of the data analysis technique and give some hints concerning future work.

 

## II. FUNDAMENTALS

### A. The best path algorithm

The short-time Fourier transform (STFT) of a given signal $s(t)$ is defined as

$$T_s(t,\nu;h)=\int_{-\infty}^{\infty} s(u)h^*(u-t)e^{-j2\pi\nu u}du, \tag{1}$$

where $t$ is the time, $\nu$ is the frequency, and $h(t)$ is a short time analysis window. As $h^*(u-t)$ effectively supresses the signal outside a range around the analysis point $u=t$, the STFT is a *local* spectrum of $s(t)$ around $t$. The spectrogram is obtained by taking the squared magnitude of the STFT.

In order to recover the slow $f_b$ component we developed a new technique consisting of the application of Floyd's best path algorithm to the spectrogram.

Floyd's best path algorithm works as follows. Given a set of nodes $G_i$, $i=1,...,n$ and a length matrix $L_{ij}$, where $L_{ii}=0$, $L_{ij}\geqslant 0$ if $i\neq j$ and $L_{ij}=\infty$ if the nodes $i$ and $j$ are not connected, Floyd's algorithm returns the length of the shortest path between each pair of nodes $(i,j)$ in matrix $D_{ij}$ and the shortest path between them in matrix $S_{ij}$. To find the shortest path between any given nodes $i$ and $j$ one looks at $S_{ij}$. If $S_{ij}=0$ the shortest path is the direct path between $i$ and $j$; otherwise, if $S_{ij}=k$ the shortest path from $i$ to $j$ passes through node $k$. By looking recursively at $S_{ik}$ and $S_{kj}$ we can find other intermediate nodes, if they exist, along the shortest path.

The new technique takes into account the main and secondary spectrogram peaks and has the following steps:

(1) Let $h_j$ be the $j$th analysis window, $A_{j_{\max}}$ the amplitude of the main spectral peak within $h_j$ and $P_j$ the set of peaks from $h_j$ that verify the condition $(1-\delta)A_{j_{\max}}\leqslant A_i \leqslant A_{j_{\max}}$, where $A_i$ is the peak amplitude and $0<\delta<1$ is an adjustable peak selection parameter.

(2) Build a set of nodes by connecting every peak in $P_j$ to every peak in $P_{j+1}$; the distance between each pair of nodes is given by the frequency gap between the corresponding peaks.

(3) Apply the Floyd best path algorithm to the set of nodes in order to find the beat frequency path that minimizes the (frequency) distance between the start and end peaks.

In the case of multiple start and/or end peaks we have two alternative solutions: to apply the algorithm successively to each possible path and to choose the best one or to choose the start and end peaks closer (below and above, respectively) to the median beat frequency. While the first solution may be computationally expensive (in the case of a big number of start/end peaks) the second may fail for severely damaged reflectometry signals. However, in the later case, the sample is most likely to be rejected (see Sec. II B) and therefore we adopted the second solution.

### B. Data validation and rejection

When broadband reflectometry signals are severely corrupted by fluctuations it makes no sense trying to reconstruct the density profile. In such cases the best option is to reject the sample so that it will not influence further processing.

To automatically validate/reject each sample we use the statistics of the group delay curve. For each sample, the mean standard deviation $\sigma$ of the $\tau_g(F)$ curve is computed (after its trend has been removed). A given data point $\tau_g(F_i)$, where $F_i$ is the $i$th probing frequency is rejected, if $\tau_g(F_i)\notin ]-w,w[$, where $w=\alpha\sigma$ and $0<\alpha<1$ is an adjustable parameter. After all data points have been tested the complete sample can be rejected if $N_{\text{rem}}<\beta N$. $N_{\text{rem}}$ is the number of nonrejected data points, $N$ is the total number of points in the $\tau_g$ curve and $0<\beta<1$ is another adjustable parameter. The parameters $\alpha$ and $\beta$ are *a priori* adjusted based on tests performed with data obtained in several plasma regimes; typical values are in the range 0.8–1.0 for $\alpha$ and 0.65–0.85 for $\beta$.

### C. Profile inversion

The density profile can be inverted (from $O$ mode) using the Abel inversion integral,

$$R(F)=R_0-\frac{c}{\pi}\int_0^F \tau_g(f)\,\frac{df}{\sqrt{F^2-f^2}}, \tag{2}$$

where $R(F)$ is the location of the plasma reflection layer corresponding to the probing frequency $F$, $R_0$ is the position of the plasma edge $[n_e(R_0)=0]$, and $c$ is the speed of light.

For profile initialization, we follow the procedure outlined in Ref. 5 with the $\tau_g(F)$ curve corresponding to the nonmeasured part of the edge plasma, $0\leqslant F<F_1$ where $F_1$ is the first probing frequency, modeled by

$$\tau_g(F)=A\left(\frac{F}{F_1}\right)^2 \exp\left[B\left(\frac{F}{F_1}\right)\right], \tag{3}$$

where $A=\tau_g(F_1)\exp(-B)$ and $B=[F_1|(\partial\tau_g/\partial F)(F_1)|-2\tau_g(F_1)]/\tau_g(F_1)$. Further details about the model used may be found in Ref. 6.

The density profile below the first layer reflecting $O$ mode, $n_{e_1}(F_1)$, can also be obtained with $X$-mode probing. However, for faster and simpler profile evaluation (no data from the magnetic diagnostics is required) we determined typical values for $R_0$ from $X$ mode and use these to calibrate the group delay curves for the path between the antenna and $R_0$. A systematic comparison of the results obtained with the initialization model and $X$-mode probing is presently being made.

## III. EXPERIMENTAL RESULTS

### A. Automatic density profile evaluation

Figures 1(a) and 1(b) illustrate the application of the different techniques (peak, first moment, and best path) to two signals obtained with the Ka band (26–36 GHz) reflectometer. In both cases, a small asymmetric perturbation is observed for $F\sim 28$ GHz causing the curves corresponding to the first moment to be slightly displaced. For $F \geqslant 31.8$ GHz the signals are strongly disturbed and the main peak curve is shifted to lower frequencies that do not correspond to the plasma profile. In this case the first moment also

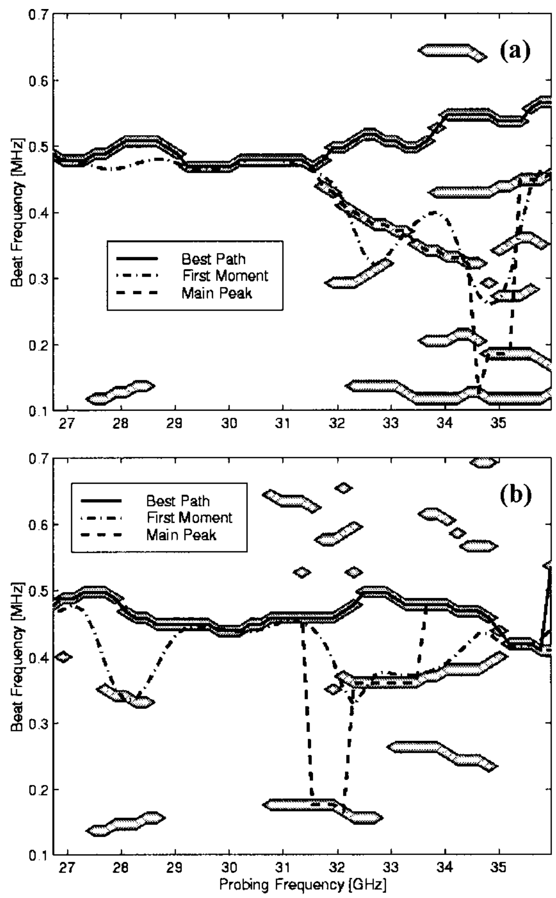


FIG. 1. Application of the three different methods (main peak tracking, first moment, and best path) to two Ka band signals.

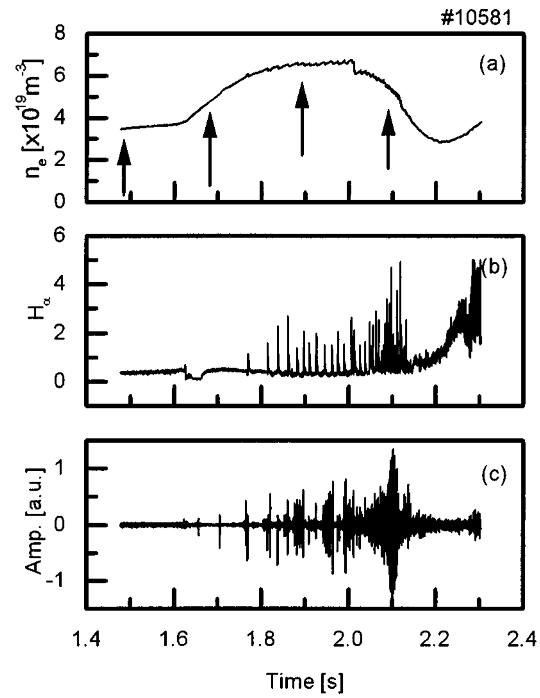


FIG. 3. Evolution of (a) average density, (b) $H_\alpha$ radiation, and (c) data from odd-$n$ channel of the Mirnov coils during the ASDEX upgrade density limit shot 10 581. The arrows in (a) indicate the time windows where reflectometry measurements were performed.

deviates from the correct values. In both situations the best path method was able to recover the correct $f_b$ curves.

Figure 2 shows an example of profile measurements performed during several plasma regimes in the density limit shot 10581 ($\overline{n}_{e_{\max}}=6.8\times10^{19}\ \mathrm{m}^{-3}$), at both the low (LFS) and high magnetic field sides (HFS). Figure 3 shows: (a) the evolution of the average density as given by the DCN interferometer, (b) the signal from the $H_\alpha$ radiation monitor, and (c) magnetic data from the odd-$n$ channel of the Mirnov coils. The time windows of the reflectometry measurements, indicated by the arrows in Fig. 3(a), were taken at the ohmic and $H$-mode phases (ELM free and ELMy). In the last time window an $m=2$, $n=1$ rotating tearing mode was present, [Fig. 3(c)]. At the low field side the corresponding reflectometry signals exhibit a high level of perturbations; at the high field side these are much lower but when the rotating mode is present an increase is observed that can be seen in the reconstructed profile (Fig. 2). A comparison between two profiles obtained during the ohmic phase from both the Li-

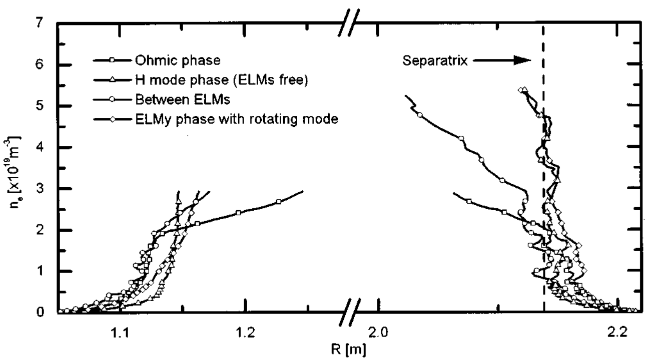


FIG. 2. Profile measurements performed during several plasma regimes in the ASDEX upgrade density limit shot 10 581 ($\overline{n}_{e_{\max}}=6.8\times10^{19}\ \mathrm{m}^{-3}$) at both the low and high magnetic field sides.

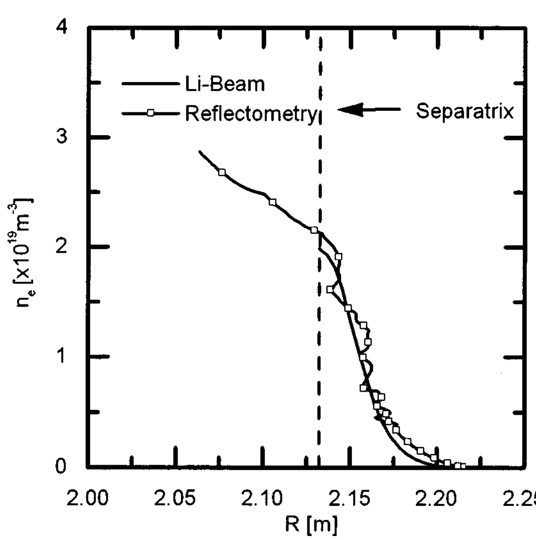


FIG. 4. Comparison between reflectometry and Li-beam profile measurements performed during the ohmic phase in the ASDEX upgrade density limit shot 10 581.

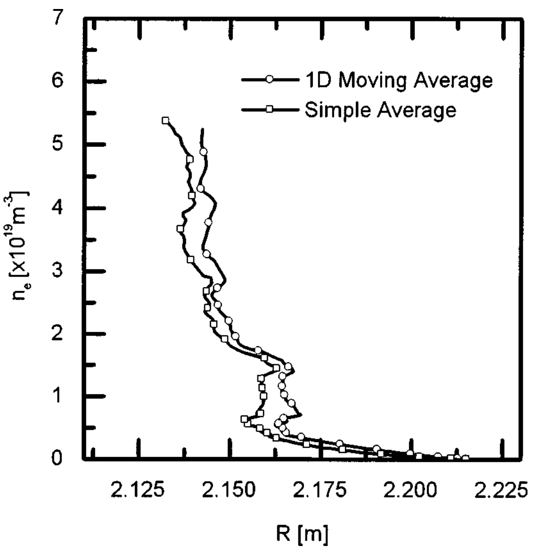


FIG. 5. Comparison between profiles obtained using a simple and a moving average.

beam diagnostic and reflectometry using with the new technique is presented in Fig. 4. The results show a good agreement.

If should be noted that for this shot the signals of the $V$ band reflectometer at the high field side (probing $n_e \geqslant 3 \times 10^{19}\ \mathrm{m}^{-3}$) could not be used due to the saturation of the detection amplifiers. Nevertheless this example was selected because the different phases of the plasma were sampled in the same shot. But, as the level of fluctuations at the HFS is always significantly lower than that at the LFS, the viability of the automatic profile evaluation under strong density fluctuations could be demonstrated.

### B. Data averaging

One way to decrease the variance of the reconstructed density profiles (increase in precision) is to average the group delay curve over a number of consecutive sweeps. If a simple average is used a compromise has to be done between precision and temporal resolution due to the profile changes. An alternative method consists of the application of a moving average window to the set of consecutive sweeps. Due to its *local* behavior the moving average allow us to decrease the variance while retaining a good temporal resolution. However, care should be taken to adapt the width of the average window to the degree of correlation between consecutive samples.

Figure 5 shows the application of the two methods to a set of 24 consecutive sweeps (sweep time 100 $\mu$s, sweep interval 100 $\mu$s) obtained in the ELM free $H$-mode phase of shot 10 581. The simple average was computed over the 24 sweeps while the moving average was obtained from only five consecutive sweeps. As expected the simple average curve has the lower variance but it deviates significantly from the *local* average profile obtained, at the cost of a small increase in variance, with the moving average.

Averaging is also possible in the spatial direction by means of a two dimensional moving average window.

## IV. DISCUSSION

The new technique here presented for the evaluation of density profiles from broadband reflectometry is able to recover the average profile in a wide range of plasma regimes, under high levels of plasma fluctuations and when the profile is disturbed by a rotating magnetic mode. The method does not require narrow filtering or any fine adjustment of parameters. It is rather based on decision criteria that use the complete information of the local energy spectrum and takes into account the time history and the statistics of the group delay curve. This permits us to validate (or reject) the data with great confidence and to recover the detailed shape of the plasma profile provided by the reflectometry measurements. Moving averaging over consecutive sweeps is also possible which lowers the variance of the profile while retaining temporal resolution. The new technique is being extensively tested in situations where fast density changes occur (e.g., during ELMs).

Further improvements to the technique can still be done. The most important is the use of kernel decomposition in the spectrogram computation that will permit us to speed up the calculations, which is very important for data processing between shots.

## ACKNOWLEDGMENTS

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