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Measurement of Fast Density Profile Changes by FM Broadband Reflectometry on ASDEX Upgrade

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1 Introduction

Plasma discharges near the density limit show fast electron density profile changes which are studied with microwave reflectometry: Near the density limit the discharge becomes MHD unstable leading to growing magnetic tearing modes. These magnetic islands strongly modulate the shape of the electron density profile. From the form of the profile the modes present can be determined. After the density limit marfes, which are cold and dense plasma clouds, occur, leading to a fast steepening of the density profile on the High-Field side of the tokamak.

2 Method

The results presented here were obtained with the Frequency Modulated (FM) broadband reflectometry system on ASDEX Upgrade in O-mode polarization [1]. The microwave frequencies launched to the plasma were swept between 16 and 72 GHz in 100 μs (20 μs are possible) corresponding to probed cut-off densities of $0.3 - 6.4 * 10^{19}\ m^{-3}$. The density profiles are determined by calculating the distance $\Delta R(f)$ between the cut-off layer and the beginning of the plasma, depending on the microwave frequency f, by

$$\Delta R(f) = \frac{c}{2\pi^2} \int_0^f \frac{d\varphi}{df'} \frac{df'}{\sqrt{f^2 - f'^2}} \qquad (1)$$

(c: speed of light in vacuum, f': integrating variable). φ is the phase difference between the microwave reflected from the plasma and a reference signal. The group delay $d\varphi/df'$ of the results presented here is calculated with an algorithm determining in a first step the zero crossings of the interference pattern, obtained by correcting the raw signal for the internal reflections and then symmetrizing around zero, combined in a second step with a statistical analysis to improve signal quality (fig. 1). This analysis can be combined with other algorithms for determining the group delay, as the minimum-maximum method [2], or the digital frequency discriminator [3]. In order to remove fringe count errors, the zeroes found in a first step are analysed concerning their statistical significance. The criterium used here is given by the Poisson statistics describing the noise of the detector system. If the standard deviation $\sigma_{\Delta f}$ of the frequency distances Δf_i of neighbouring zeroes (labeled with the index i) is bigger than their mean distance $\overline{\Delta f}$, they are detected as noise and removed. For the calculation of

$$\overline{\Delta f} = < \frac{\Delta f_i}{\Delta f_r} >, \qquad \sigma^2_{\Delta f} = < \left(\frac{\Delta f_i}{\Delta f_r} - \overline{\Delta f} \right)^2 > \qquad (2)$$

(< . > denoting the average over a group of typically 7 neighbouring zeroes) the frequency resolution Δf_r determined by the number of acquired microwave frequencies per sweep must be specified. This algorithm seems to have great potential to determine the group delay in case of low signal to noise ratio: Since it principally analyses only small parts of the whole frequency sweep for good signal quality the noisy parts in a sweep are cut out. The gap in the data is closed by interpolating from the neighbouring valid data points. For flat profiles where there is no interference pattern at the higher frequencies, the point where the signal disappears below the noise level is determined and the profile evaluation ends (see fig. 1).

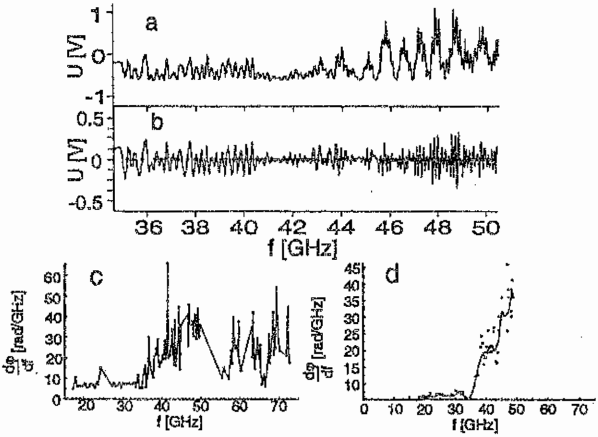

Fig. 1: Correcting the raw data of a frequency sweep with plasma (a) for the internal reflections (obtained without plasma) and then symmetrizing around zero, the interference pattern from the plasma is obtained (b). The group delay $d\varphi/df$ *shown in (c), is calculated from the signals (b). The noise in* $d\varphi/df$ *stems from the fringes of small amplitude. These parts are removed after the application of the statistical analysis. The result, which is also corrected for delays between the reflected and the reference signal, is shown in (d). This group delay is used for the evaluation of the electron density profile.*

The initialization of the electron density profile is based on the measured group delay of the microwaves with the lowest frequencies [4]: Here, the distance of the plasma from the antennas, which can vary during a discharge, is estimated in this way. The group delay corrected for the vacuum distance is then used for calculating the profile.

3 Electron Density Profiles for a Density Limit Discharge

In the following, electron density profiles for an Ohmic density limit discharge on ASDEX Upgrade (plasma current 600 kA, toroidal magnetic field – 2 T), showing the occurence of a marfe and fast changes due to MHD activity, are studied.

3.1 Occurence of a Marfe

A marfe [5] starting after the density limit in the divertor and moving up to the equatorial plane of the plasma on the High-Field side of the tokamak can be clearly identified by the steepening of the density profile: the profile of the pre-marfe phase shows within milliseconds a strongly increased particle content and a steepening of the gradient outside the separatix (fig. 2). This coincides with an increase of the Bremsstrahlung intensity in the near infrared, viewing the equatorial plane of the plasma. After this, the marfe is moving to the inside of the plasma (time 1.93805 s) in accordance with an increase in the Bremsstrahlung intensity, due to the higher density of the marfe.

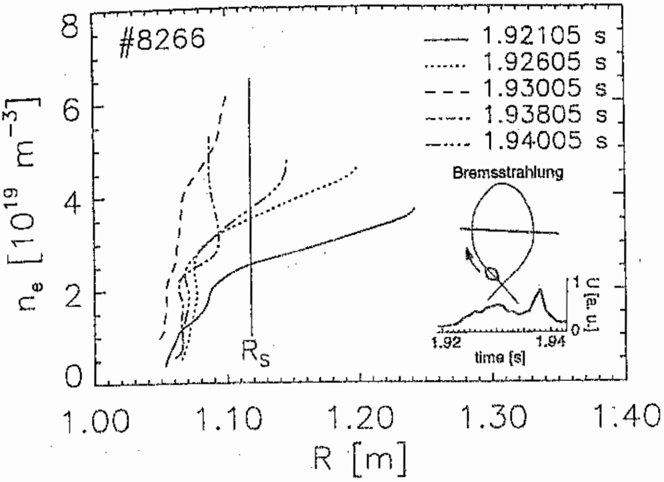

Fig. 2: A marfe occurs on the High-Field side in the equatorial plane of the plasma between the times 1.923 s and 1.941 s, as seen in the Bremsstrahlung intensity U, plotted in the insert picture. The electron density profiles measured with the reflectometry system on the High-Field side shows an increase of the gradient of the electron density profile outside the separatrix, positioned at R_S*, compared to the pre-marfe profile at 1.92105 s. The marfe is at the centre of the sightline at 1.930 s (steepest density gradient) in accordance with Bremsstrahlung. After this the marfe is moving to the inside of the plasma (1.93805 s) reflected in the peaking of the Bremsstrahlung intensity due to higher density of the marfe. At around 1.94005 s the marfe is leaving the region of observation, leading to a flattening of the density profile.*

3.2 Identification of m=4 and m=5 Modes

After the density limit mode locking occurs at the time 1.858 s. From analysing the magnetics data in the phase before locking the m=2 and m=3 modes were found to be present. When the island widths are growing nonlinear coupling of the modes gives rise to the generation of modes of higher poloidal wave number (m=4, m=5). After mode locking has occured, the mode structure can not be inferred by the magnetics. The m=4 and m=5 modes are, however, detected in the electron density profiles, when the mode structure starts moving around its locked position (fig. 3): The earliest profile in the following series (fig. 3) at the time 1.85905 s (now termed 1. profile) is still unperturbed. The 2. and 3. profile shows a flattening at the q=5 flux surface shifting the steep gradient zone to the q=4 surface (the q-profile used here was reconstructed from magnetic measurements). The flattening is extended up to the q=4 flux surface in the 4. and 6. profile. The 5. profile shows an unperturbed shape similar to the 1. profile. So the fast flattening and steepening of the profiles is observed repetitively. From the varying shapes of the electron density profiles the m=4 and m=5 modes are identified to be present.

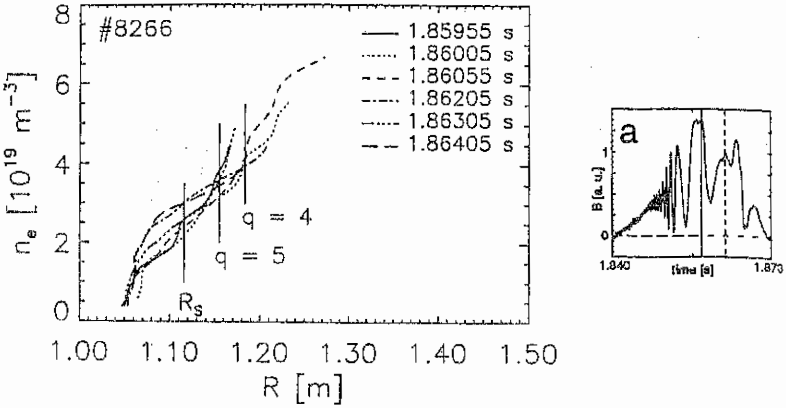

Fig. 3: Mode locking occurs at the time 1.858 s *as can be seen in the perturbed poloidal magnetic field (a). After this the coupled mode structure is moving around its locked position. In the electron density profiles (shown until 1.86405 s corresponding to the broken line in (a)) the m=4 and m=5 modes can be detected after mode locking: the earliest (1.) density profile is still unperturbed followed by a flattening of the density profile around the q=5 surface (2. and 3. profile), extending in the 4. and 6. profile also up to the q=4 surface, interrupted by the 5. profile showing the unperturbed form. So the flattening and steepening of the profile is repetitive. The position of the magnetic separatrix is denoted by* R_s. *The q-profile was reconstructed from magnetic measurements.*

4 Conclusion

The applied algorithm for the determination of density profiles is flexible enough to resolve density profiles of different shape. It has great potential to recover profiles also from noisy signals. It is presently used for fast automatic routine evaluations on ASDEX Upgrade. The time history of the position and the density gradient of a marfe occuring on the inboard side of the tokamak is presently directly measured only by the microwave diagnostic installed there. After the locking of tearing modes, a flattening and steepening of the electron density gradient can be observed at rational q-surfaces, ascribed to a movement of the modes around their locked positions.

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