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The impact of inverted density gradients on density profiles measured by reflectometry: an experimental and numerical investigation at ASDEX Upgrade

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Abstract: The high-field side high-density (HFSHD) region at ASDEX Upgrade (AUG) is a well-documented phenomenon leading to a dense plasma in the inner divertor region that expands upwards to the midplane, resulting in poloidally asymmetric scrape-off layer density profiles. This work investigates, via simulation and experiment, whether the HFSHD at the midplane leads to hollow density profiles at the high-field side. Using the frequency-modulated continuous-wave O-mode reflectometer at AUG, experimental evidence has been found of reflection patterns compatible with a hollow density profile that are reproduced by 1D full-wave simulations. Furthermore, this work assesses the uncertainties in the density profile reconstruction as a consequence of the inverted gradient, showing that the presence of an HFSHD may lead to an overestimation of the density in the confined region.

Keywords: Reflectometry; microwave reflectometry; high-field side; high-field side high-density; high-field side high-density front; density profile; density profile reconstruction; density measurement; density profile measurement; ASDEX Upgrade; poloidal asymmetry; O-mode reflectometry; plasma diagnostics; full-wave simulation.

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1 Introduction

At ASDEX Upgrade (AUG), the detachment of the inner divertor is associated with the existence of a high-field side high-density (HFSHD) region in the divertor [1]. The HFSHD region expands to the high-field side (HFS) midplane, leading to strong poloidal asymmetries in the scrape-off layer (SOL) density [2]. This HFSHD region has been recovered in the modeling of AUG plasmas with SOLPS 5.0 [3], also showing a clear in-out asymmetry of the SOL density profiles. SOLPS modeling has also predicted an inverted density gradient at the inner midplane separatrix and a hollow profile with a density peak outside the separatrix. The HFSHD in the divertor region has been extensively characterized on AUG using mainly spectroscopic measurements [1]. The position of the high-density region is known to change during the discharge between the far- and near-SOL, responding to the different divertor conditions. First measurements by the divertor Thomson scattering diagnostic recently installed in AUG have also shown hollow density profiles with a local maximum in the HFS SOL away from the separatrix [4]. Therefore, the HFSHD leads to non-monotonic density profiles at the HFS with a hollow part (local minimum) near the separatrix.

In principle, O-mode reflectometry is unable to probe the hollow part of the density profile due to wave reflection at the higher density in front of it. The HFS reflectometer is blinded by a region with a negative density gradient (decreasing density moving away from the limiter) in the vicinity of the separatrix caused by the existence of the HFSHD in the HFS SOL. Hence, the existence of a hollow region leads to discrepancies between the real density profiles and those measured with O-mode reflectometry using conventional reconstruction techniques [5].

This contribution investigates - via simulation and experiment - the existence of hollow density profiles at AUG associated with the HFSHD region. On the simulation side, a synthetic O-mode reflectometry diagnostic was implemented based on a 1D full-wave code [6]. On the experiment side, our work leveraged the unique capability of the AUG frequency-modulated continuous-wave (FMCW) O-mode reflectometer [7, 8] to measure radial density profiles simultaneously at the low-field side (LFS) and HFS. This study is a step toward better understanding the signature of a hollow profile in the spectral content of the FMCW O-mode reflectometry measurements.

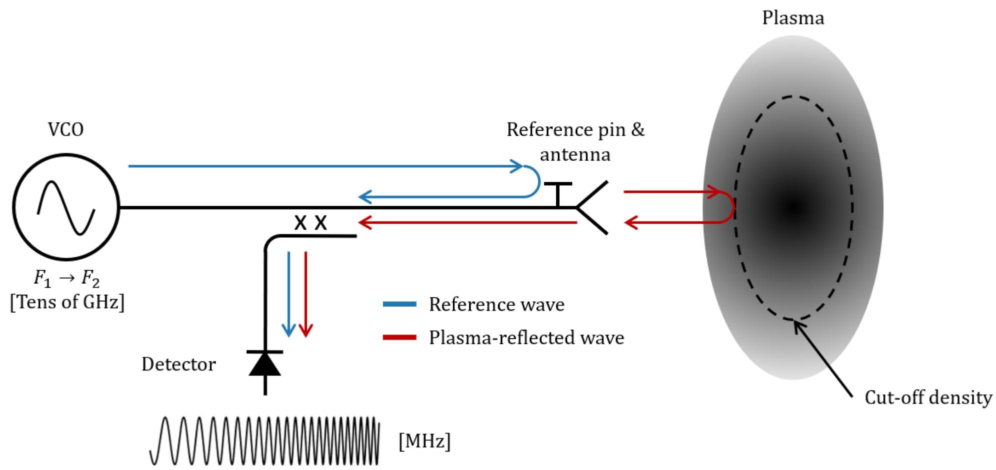

Figure 1. Schematic illustration of the FMCW O-mode reflectometer at AUG.

2 Reflectometry measurement technique and signal analysis

This paper pivots on the measurement of edge electron density profiles using O-mode microwave reflectometry. The O-mode profile reflectometer at AUG uses a frequency-modulated continuous-wave to probe the plasma in the equatorial plane and has the unique capability of simultaneously measuring the density profiles at the HFS and LFS of the machine. For the discharges studied here, the reflectometer measured in the density range $0.3 - 3.0 \times 10^{19}\mathrm{m}^{-3}$, which corresponds to 17-50 GHz in terms of probing frequency. The frequency range is split into three bands: K (17-25 GHz), Ka (25-37 GHz), and Q (37-50 GHz).

O-mode reflectometry uses the reflection of ordinary waves in the plasma to determine the position of each successive density layer [9]. Figure 1 shows a simplified representation of the AUG FMCW O-mode reflectometer. A voltage-controlled oscillator produces microwaves with a frequency ramp. The same antenna is used to launch and receive the waves reflected at the corresponding cutoff plasma layer where the plasma frequency matches the wave frequency. Since the oscillator frequency is being swept, the plasma-reflected signal lags behind the reference signal in frequency. After mixing the two signals and applying a low-pass filter, a beat signal is produced that allows for the localization of the probed density layers.

In addition to the reflectometry diagnostic, our investigation resorted to a synthetic version of this diagnostic implemented on a finite difference time domain electromagnetic solver in one dimension [6]. Our synthetic diagnostic is able to produce the raw signal that is measured experimentally (the beat signal) for an arbitrary density profile.

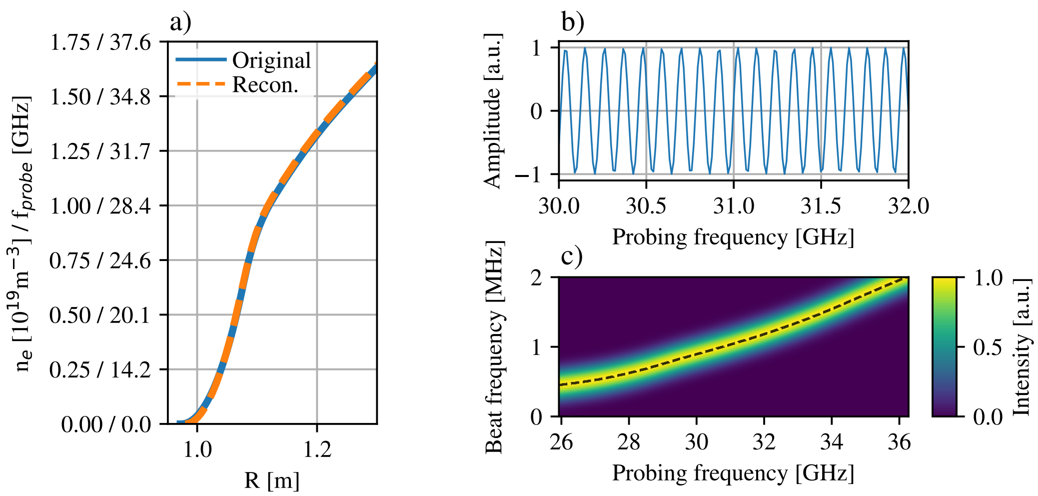

Figure 2. Illustration of the density profile inversion workflow: **a)** Input (blue) and reconstructed (dashed orange) density profiles; **b)** Beat signal output from the simulator (only shown between 34 GHz and 36 GHz); **c)** spectrogram of the beat signal in the Ka-band. The black dashed line represents the dominant beat frequency that is used to reconstruct the density profile.

Figure 2 shows an example of the density profile reconstruction workflow. For this example, we use the synthetic reflectometer - based on the 1D full-wave code - to calculate the beat signal (2b) produced by the density profile in 2a. The lag of the reflected wave - group delay (τ) - is extracted from the spectrogram of the beat signal (figure 2c). The group delay is calculated by taking the beat frequency of highest intensity for each probing frequency (black dashed line in 2c) and dividing it by the sweep rate of the microwave ramp $\partial f/\partial t$. Finally, the estimated density profile is obtained from equation 2.1:

$$r(f_{\text{probe}}) = \frac{c}{\pi}\int_0^{f_{\text{probe}}} \frac{\tau(f)}{\sqrt{f_{\text{probe}}^2 - f^2}}\mathrm{d}f \tag{2.1}$$

using the group delay τ for each probing frequency f, where $r(f_{\text{probe}})$ is the radial location of the cutoff density layer for the frequency f_{probe} [9]. A comparison of the original and reconstructed density profile is depicted in figure 2a, showing the reconstructed density profile overlaid with the original.

3 LFS/HFS density asymmetries in the confined region

In this study, we use measurements obtained in AUG discharges with line-averaged density ramps at -2.5 T / 0.8 MA in L-mode. The discharges presented here (#34092, and #35145) are ERCH-only heated at 0.3 MW, and 0.4 MW, respectively and are both in LSN configuration with a small upper triangularity (0.05 and 0.10, respectively). This work is focused on the formation of the HFSHD along the density ramp and its effect on the reconstruction of the density profiles measured by reflectometry.

Usually, edge density profiles measured by reflectometry at the midplane in the confined region are only poloidally symmetric at low line-averaged density - typically below $3 \times 10^{19}\text{m}^{-3}$. Above this value, HFS/LFS asymmetries are regularly observed [2].

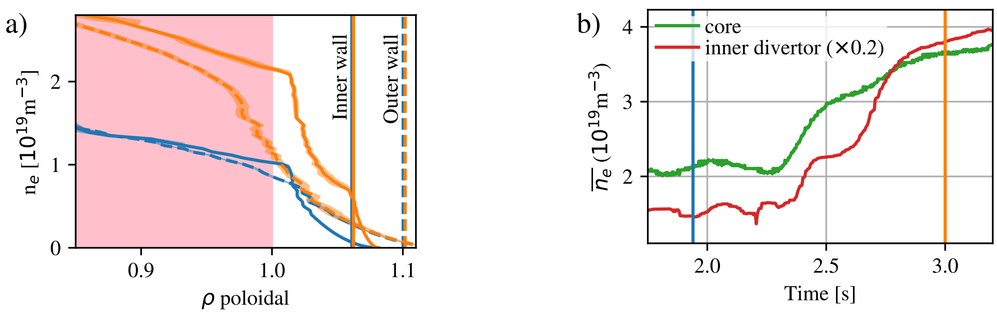

Figure 3. **a)** Radial density profiles from reflectometry at HFS (solid lines) and LFS (dashed lines) at 1.94 s (blue) and at 3.0 s (orange) for discharge #34092. The position of the inner and outer walls are indicated by the vertical lines. **b)** Line-averaged density at the core measured by interferometry, and at the inner divertor measured by Stark broadening spectroscopy [10]

Figure 3a shows the radial density profiles at the HFS and LFS for discharge #34092 from reflectometry for two discharge periods with different values of line-averaged density (2.1 and $3.6{\times}10^{19}\text{m}^{-3}$). As expected, at low densities, the midplane density profiles in the confined region are poloidally symmetric. As the line-averaged density rises, the SOL density increases faster at the HFS than at the LFS, leading to SOL poloidal asymmetries as reported in [2]. This is caused by the development of the HFSHD in the divertor as demonstrated by the evolution of the density in the inner divertor volume measured by stark broadening spectroscopy [10], which expands to the midplane SOL, see figure 3b).

For the discharges studied here - L-mode with low ECRH power - no significant HFS/LFS asymmetries in the electron density profile are expected in the confined region. Therefore, assuming that the density profiles are indeed HFS/LFS symmetric, we will consider as a working hypothesis that the observed asymmetry in the confined region is not real, but it is instead due to profile reconstruction limitations in the presence of a blind area in the density profile.

4 Simulation of hollow density profiles

A way of accommodating the existence of an HFSHD in the SOL with symmetric LFS/HFS density profiles in the confined region is to assume that the radial density gradient is negative in the vicinity of the separatrix, leading to a hollow density profile.

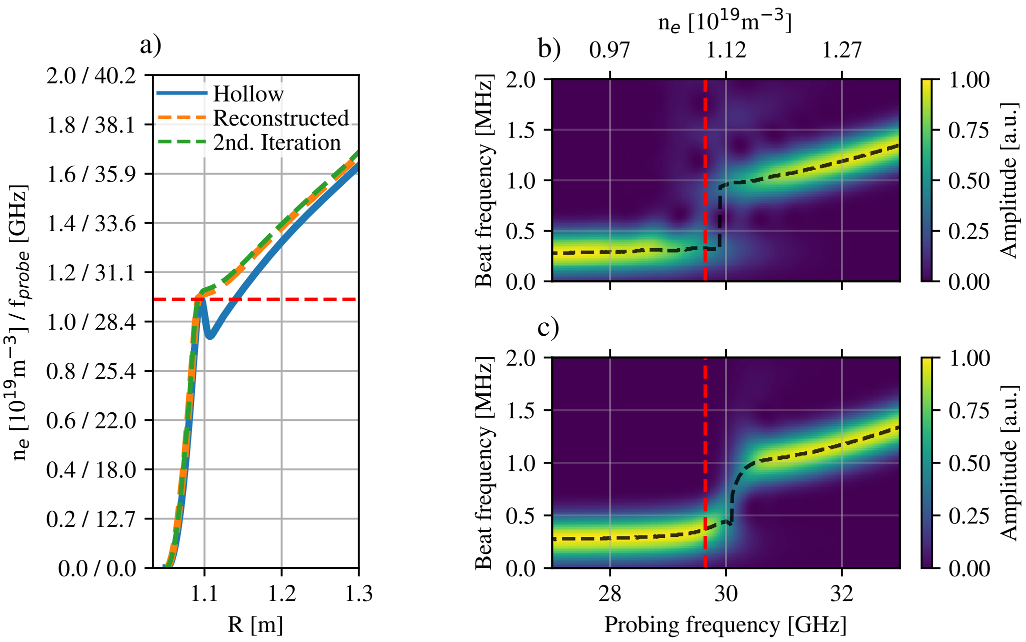

Figure 4. **a)** Hollow density profile used as input to the 1D full wave code (blue), and reconstructed density profiles using the group delay obtained in b) and c) (dashed orange and dashed green respectively). **b)** Spectrogram of the beat signal output by the simulator for the hollow profile. The dashed black line represents the maximum intensity for each probing frequency that is then used to compute the group delay and reconstruct the density profile in dashed orange. **c)** Spectrogram of the beat signal obtained from the reconstructed density profile (dashed orange) that is then used to obtain a second iteration profile (dashed green). The red dashed lines correspond to the density/frequency of the density peak.

Figure 4 illustrates how the existence of a hollow density profile results in artifacts in the profile reconstruction. The blue profile shown in figure 4a is used as input of the 1D full-wave code, which outputs the corresponding interference beat signal. The beat signal is then analyzed in the frequency domain using a spectrogram, or sliding fast-Fourier transform, as shown in figure 4b, which illustrates the variation of the beat frequency with probing frequency. The group delay curve (black dashed line) is then estimated using the beat frequency of maximum intensity for each spectrogram window. Finally, the group delay is used in the Abel inversion equation to obtain the reconstructed density profile (dashed orange line in figure 4a). As anticipated, the reconstructed density profile differs significantly from the input profile due to the existence of a blind area for the probing waves, leading to an overestimation of the density in the confined region.

For comparison, the reconstructed density profile (dashed orange in 4a) is also used as input in the simulator with the obtained spectrogram presented in figure 4c). The spectrograms of the original and reconstructed profiles (figures 4b,c) differ only near the 30 GHz probing frequency in the vicinity of the local density maximum. In the presence of a blind region, the spectrogram exhibits a large discontinuity in the group delay (figure 4b) with a significant power level observed at two beat frequencies (0.3 and 1.0 MHz) for the same probing frequency ($\approx$ 30 GHz). These beat frequencies correspond to waves that interact with the structure of the well either by tunneling through the HFSHD or by being partially reflected by the sharp local maximum of the refractive index. In contrast, the spectrogram corresponding to the monotonic density profile (figure 4c) shows no discontinuity in the group delay and no other beat frequencies beyond the main reflection. Nevertheless, the profiles reconstructed from both spectrograms (dashed green and dashed orange in 4a) are almost indistinguishable since the reconstruction procedure only uses the maximum intensity of the spectrogram for each probing frequency. The small differences in the obtained group delay are smeared out by the Abel inversion process. The fact that the two profiles (hollow and monotonic profiles) are only distinguishable at the spectrogram level draws our attention to the importance of its detailed study in the experiment.

Although different density profiles may give rise to similar group delay characteristics, a hollow profile has an easily distinguishable spectrogram signature that sets it apart from a monotonic one. The following section will show how this same signature shows up in experimental data, supporting the hypothesis of a hollow density profile.

5 Experimental evidence of inverted density gradients at the HFS

Discharges with a density ramp are suitable candidates to look for experimental evidence of inverted density gradients caused by the HFSHD since the magnitude of the HFSHD is dictated by, among other factors, the average discharge density [11]. Figure 5 shows the evolution of the electron density radial profiles at the LFS and HFS, together with images from visible radiation cameras looking at the inner wall and divertor region for selected times along a density ramp discharge. As the line-averaged density increases, the LFS/HFS asymmetry of the density profiles becomes stronger, likely due to the increase in the HFSHD magnitude. The HFSHD evolution is also evident in the camera images showing an increase in the radiation in front of the inner wall along the density ramp.

The spectrograms of the beat signal from the HFS profile reflectometer presented at the bottom of figure 5 show evidence for the existence of hollow density profiles in agreement with the simulation results, namely a large discontinuity in the group delay and significant reflected power at two distinct beat frequencies for the same probing frequency compatible with wave tunneling. In

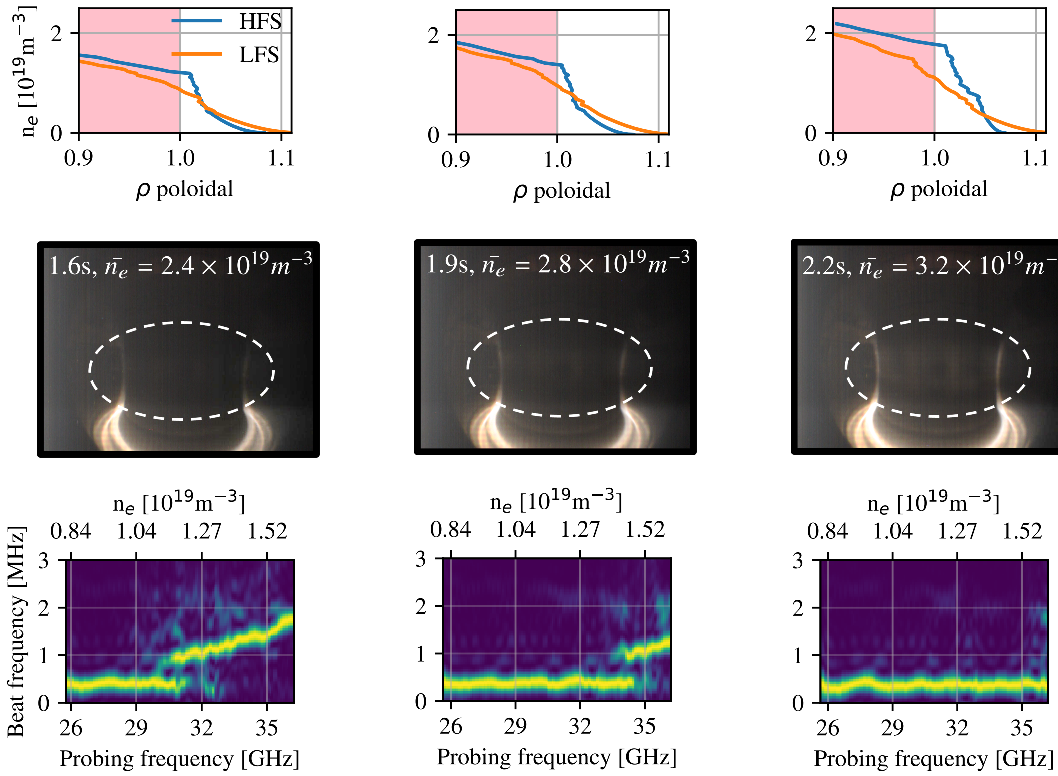

Figure 5. Evolution for selected times along a density ramp discharge (#35145) of the density profiles both on the LFS and HFS (top row), visible light cameras looking at the inner wall and divertor region (middle row) and spectrograms of the reflectometry beat signals from the HFS (bottom row).

addition, the probing frequency at which the group delay discontinuity occurs increases throughout the discharge, as expected from the increase of the HFSHD magnitude.

To better understand the evolution of the group delay along the density ramp, the temporal evolution of the beat signal at a fixed probing frequency is analyzed. In the presence of a hollow profile, the beat frequency is expected to jump from dominant reflections in the background profile (confined region) to dominant reflections at the HFSHD (SOL) as the amplitude of the HFSHD (local density maximum in the SOL) increases throughout the discharge. This is clearly seen in figure 6b that displays the evolution of the power spectra of the HFS beat signal for a probing frequency of 33.6 GHz (n_e=1.40×10^{19}m^{-3}). The dominant beat frequency changes discontinuously when the local density maximum crosses the probed density. During this crossing, two different beat frequencies can be observed simultaneously in accordance with expected effects such as tunneling and partial reflections. Note that the density associated with the HFSHD is expected to be substantially larger in the divertor region (see figure 6a) than at the midplane, justifying that at the time of the group delay jump, the inner divertor density is much larger than the probed density.

For reference, the evolution of the power spectra of the LFS beat signal for the same probing frequency is also shown (figure 6c), evidencing no discontinuities in the group delay but rather a smooth decrease of the group delay along the density ramp corresponding to the outward movement of the probed density layer. These results present a clear experimental confirmation that inverted density gradients do exist at the HFS of AUG, justifying the poloidal density asymmetries observed in the confined region.

Several diagnostics are available on the LFS at AUG. Therefore, the LFS reflectometer measurements are routinely benchmarked against other LFS density diagnostics such as the lithium beam and Thomson scattering, giving us confidence in the accuracy of the LFS profiles. Thus, we are convinced that the observed LFS/HFS asymmetry is not due to uncertainties in the profile reconstruction at the LFS.

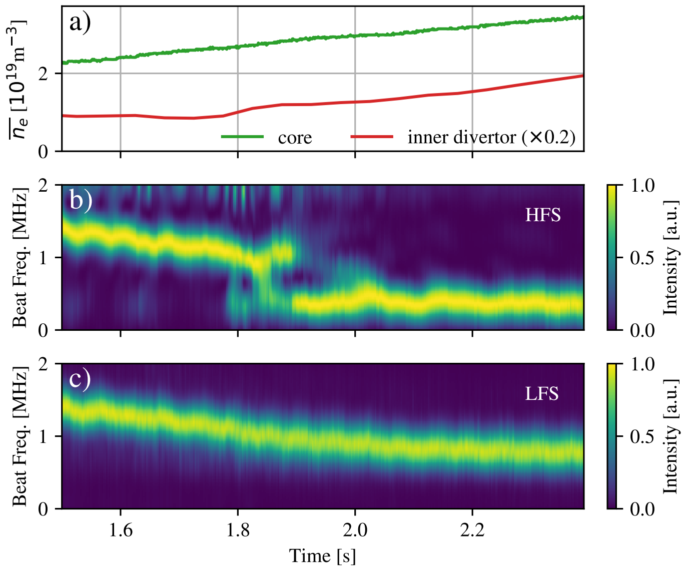

Figure 6. Data for discharge number #35145 with a density ramp. **a)** Line-averaged density at the core measured by interferometry, and at the inner divertor measured by Stark broadening spectroscopy [10]. **b) & c)** Evolution of the power spectra of the HFS (b) and LFS (c) beat signals for a probing frequency of 33.6 GHz (n_e=1.40×10^{19}m^{-3}). A reduction in the beat frequency indicates that the reflection occurs radially further out (closer to the antenna).

6 Conclusion

The electron density reconstructed from O-mode reflectometry measurements on the HFS at ASDEX Upgrade commonly exceeds the LFS density even in the confined region. However, significant density asymmetries between LFS and HFS are not expected to exist in the confined region for the regimes investigated here (L-mode plasmas without seeding).

One way to account for the asymmetry in the density profile is to assume that the HFS profile is hollow, meaning that the density decreases towards the plasma core near the separatrix because of the HFSHD region. Via simulation, we have shown that the traditional profile reconstruction method leads to an overestimation of the density behind the local maximum of the density profile in the presence of a hollow density profile. Our simulation studies showed that a hollow profile leads to multiple reflections and, consequently, multiple beat frequencies that appear simultaneously in the spectrogram of the beat signal. The results shown here demonstrate that such features - arising from the interaction between the waves and the density well - also exist in experimental data. We have shown that the experimental observation of a large discontinuity in the beat signal spectrogram and the presence of multiple beat frequencies correlate well with the evolution of the HFSHD reported by independent diagnostics such as the divertor spectroscopy.

In cases where the HFS profile is hollow, a systematic uncertainty may appear in the HFS density beyond the HFSHD. In such cases, alternative algorithms should be explored using information from the beat signal apart from the group delay. Comparing simulation and experimental results, it is evident that the density well "imprints" valuable information in the reflectometry signals. This information might allow the characterization of the density well and the reconstruction of hollow density profiles, reducing the uncertainties in the reconstruction result.

Acknowledgments

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