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Effects of Magnetic Field Perturbations on the Reconstruction of Density Profiles from X-mode and Combined O/X-mode Reflectometry

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Introduction

Swept frequency multi-channel reflectometry[1] on ASDEX Upgrade tokamak is capable of simultaneously measuring density profiles on the inboard and outboard sides, with both high spatial and temporal resolutions, from the propagation group delay $\tau_g(f) = (2\pi)^{-1}\, d\varphi(f)/df$ (where φ is the microwave phase shift after propagation through the plasma up to the cutoff layer and back). Extraordinary (X) mode channels[2,3] can provide the outermost part (SOL) of the density plasma profile while ordinary (O) mode can cover the region $n_e > 0.4 \times 10^{19}$ m^{-3}. The X-mode data is also important for the initialization of the profile reconstruction from O-mode. Here we investigate the accuracy of the profile reconstruction from O/X mode using a simulation code.

Group delay sensitivity to plasma density profile

Unlike O-mode, the refractive index μ for X-mode depends not only on density but also on the total magnetic field (the cutoff frequency is defined as $f_R \equiv \left(\sqrt{\Omega_e^2 + 4 f_p^2} + \Omega_e\right)/2$). At the very edge the plasma density is very low and hence it is important to study the sensitivity of X-mode to n_e and B_{tot} separately. Therefore we analyzed the influence on the X-mode group delay of: the density profile gradient ∇n_e, the magnetic field profile $B_{tot}(r)$ and the magnetic field errors (ripples). The sensitivity of the group delay has been defined as $s\,[\%] \equiv \frac{\Delta\tau_g^X}{\tau_{g,REF}^X}100 = \frac{\tau_g^X - \tau_{g,REF}^X}{\tau_{g,REF}^X}100$, where τ_g^X is the "perturbed" X-mode group delay, and $\tau_{g,REF}^X$ is a reference group delay that corresponds to the initially assumed n_e and B_{tot} profiles, typical of an ASDEX Upgrade H-mode discharge. We consider a reduction of 4% in the density profile gradient as well as in the magnetic field values. This B_{tot} variation is much higher than experimentally observed but is used to emphasis the differences. In fig.1a are plotted the sensitivities vs. r, corresponding to the reduced density gradient (blue line) and to the reduced magnetic field (red line). For the density gradient variations τ_g^X shows a good response to density profile changes with a sensitivity around 20% at the very edge and around -5% inside. The sensitivity to the magnetic field decrease is much lower and is only significant (around -5%) at the very edge plasma region. Concerning the ripples on the magnetic field, typical values for AUG are: radial wavelength λ_r between 1 mm and 10 cm and maximum amplitude 10 mT. Here we consider two cases with λ_r=5 cm and λ_r=1 cm with 10 mT amplitude. The magnetic field ripples create distortions in the cutoff frequency profile. For short wavelength ripples, these distortions can produce jumps in τ_g^X especially where the profile is flat. The corresponding sensitivities s, displayed in fig.1b, show a strong variation of τ_g^X. For long wavelength oscillations (blue line) τ_g^X has a main deviation at the edge (around 50%); for short wavelength oscillation (red line) τ_g^X exhibit large jumps at the edge and amplitude oscillations at smaller r.

Fig.1a - X-mode Group Delay Sensitivity

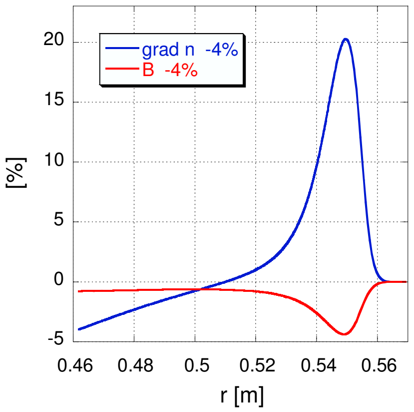
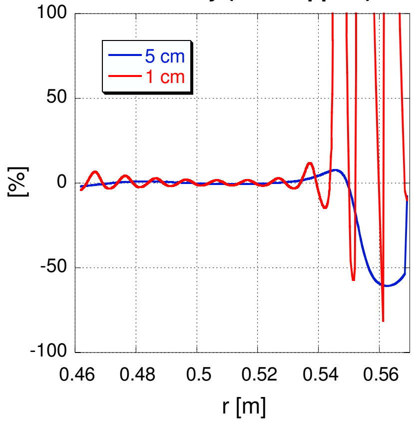


Fig.1b - X-mode Group Delay Sensitivity (with Ripples)



Reconstructed density profile

To reconstruct the density profile from X-mode group delay measurements, using an inversion algorithm, it is necessary to input the magnetic field profile (derived from magnetic diagnostics) and the value of the first fringe f_0, corresponding to the first reflectometry signal reflected from the plasma (from the cutoff layer at r_0 where the density is around zero). We studied the accuracy of profile reconstruction due to errors on the input magnetic field profile and first fringe. Since at $n_e = 0$ the first fringe frequency f_0 is equal to the electron cyclotron frequency Ω_e, r_0 can be recovered directly from the magnetic field profile. Simulations show that the main effect of varying the magnetic field is a radial translation of the density profile. However, variations in the first fringe (i.e. in steps of 200 MHz, 400 MHz, etc.) result not only in a translation of the density profile but also a modification of the profile shape at the edge. Physical restrictions limit the maximum error on the first fringe to ~2 GHz (for the density profile and the magnetic field values used in the simulation). With magnetic field variations all density layers are linearly translated with ΔB, but, for first fringe errors only the first plasma layer is linearly translated with Δf, while for the others layers the translation is not linear. That is, only the r_0 translation is linear dependent on magnetic field and on first fringe errors.

Combined O/X mode

The parameter which has the largest impact on profile accuracy is the frequency of the first fringe[4] (if there is no relevant ripples). As f_0 is often difficult to measure accurately, a new technique has been developed for profile reconstruction at the very edge based on combined O- and X-mode measurements (in the density region where they overlap) that provide corrections from first fringe data. The idea is to match the group delay τ_g^O (with contribution due to plasma and vacuum) measured from O-mode, that is independent of the magnetic field, with the group delay τ_g^X from X-mode measurement but converted to corresponding O-mode frequencies $\tau_g^{X\to O}$. This is illustrated in fig.2, where the total group delays (plasma plus vacuum) are plotted vs. O-mode frequencies. The orange line is the O-mode group delay, starting from 16 GHz, for the reference density profile; while the red line is the X-mode group delay, converted in O-mode also for the reference density profile. There is an overlapping region between 16 and 48 GHz. The blue line is obtained using for the inversion a magnetic field equal to 1.99 T (i.e. an error of 0.5%). The green line is obtained using a first fringe frequency 1 GHz more than the reference. Starting with an incorrect $\tau_g^{X\to O}$, it is possible by iterating the magnetic field and/or the first fringe, to find a match with the O-mode group delay. Simulations show that the correct values of $\tau_g^{X\to O}$ can be obtained by adjusting both f_0 and the magnetic field profile. Results reveal accurate profile reconstruction with discrepancies of less than 1 mm. Fig.3 displays an example showing the benefit of using information from X-mode ($\tau_g(f)$ from zero frequency) in the density profile reconstruction from O-mode. The comparison curve is for O-mode only with linear initialization. Both profiles start at the same r_0 but the reconstructed one with linear initialization (light blue line) shows significant differences at

Fig.2 - O/X modes Group Delays Matching

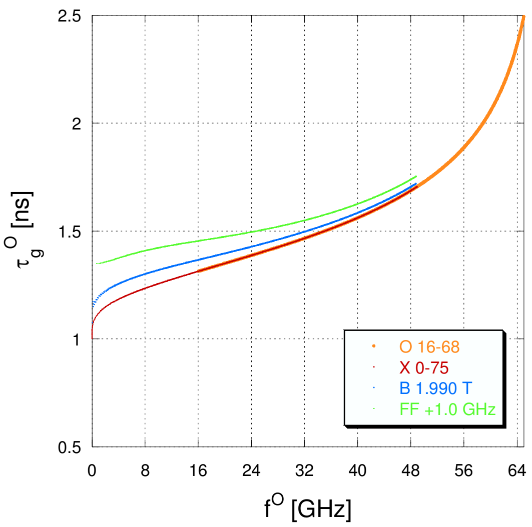
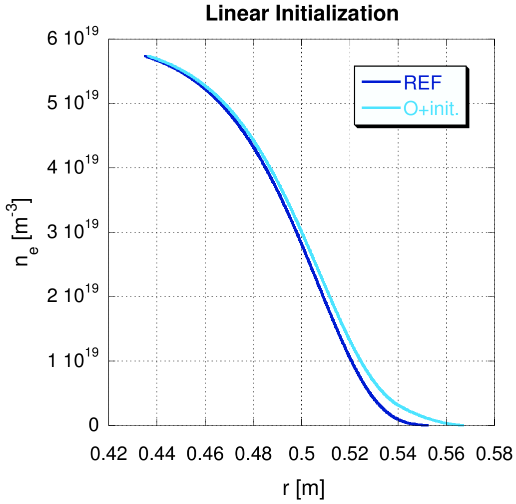


Fig.3 - Density Profile Reconstruction: O-mode plus Linear Initialization

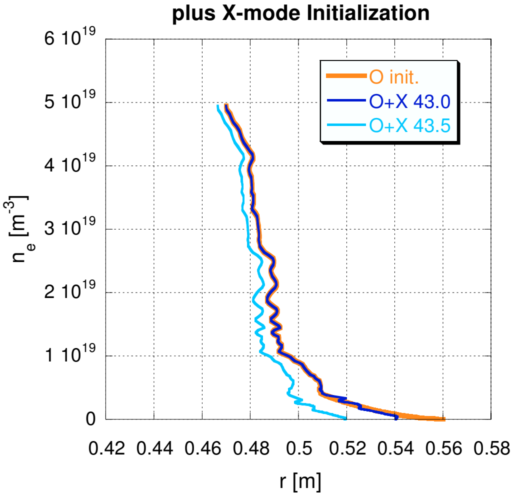


the very edge, about 1 to 2 cm. Fig.4 shows an experimental example (AUG discharge #17148) where τ_g^X is used to correct the value of f_0. The $\tau_g^X(f)$ curves are distorted due to plasma turbulence, hence a preliminary analysis gives a f_0 in the range of 43.0 to 43.5 GHz. An appropriate algorithm will be developed to extract automatically the value of f_0 and $B(r)$ to obtain the best matching between $\tau_g^{X\to O}$ and τ_g^O by minimizing the error function

$$\delta(f_0, B(r)) \equiv \sqrt{\frac{1}{m-n}\sum_{k=n}^{m}\left(\tau_g^{X\to O}(f_k)-G(f_k)\right)^2} ,$$

where G is a fit curve of τ_g^O and $\{f_{k=n,..m}\}$ the overlap frequency set.

Fig.4 - #17148 (sweep1741) Density Profile Reconstruction: O-mode plus X-mode Initialization



Final remarks

This technique of combined O/X mode reflectometry should permit the calculation of density profiles with higher accuracy. Further, it may also provide information about the magnetic field profile in the bulk plasma, by matching the O-mode and X-mode group delay curves, if the first fringe of X-mode is determined with sufficient accuracy.

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