Density profile reconstruction methods for X-mode reflectometry

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Due to the high temperatures and densities in the most advanced fusion experiments, non-invasive diagnostics are necessary to measure the plasma density. A widely employed technique for electron density is the frequency swept microwave reflectometry, based on radar systems. This project aims to improve the reconstructed profile accuracy from the data analysis standpoint, focusing in the X mode polarization. The fast and accurate determination of the density profile is crucial for real time monitoring. In addition, if the density profile is more precise, the extraction of the turbulence and transport properties will be more accurate.

In the data analysis standpoint, improvements can be investigated in three fronts: firstly, the initialization of the reconstruction; secondly, the method used to reconstruct the profile; and thirdly, the analysis of perturbations that introduce blind regions. The initialization is assumed accurate here and dedicated Full-Wave simulations will be performed to re-access the current method in use, i.e. as presented in [1, 2]. Therefore, the scope of this paper covers, initially, the reconstruction techniques, and after, perturbations in the density profile that introduce blind regions.

Reconstruction methods

The reconstruction method published by H. Bottollier-Curtet *et al.* [3] in 1987 has been the standard density profile reconstruction method in X-mode reflectometry ever since, with minor revisions. It consists in, for each frequency increment, comparing the measured phase-shift with the phase-shift numerically computed through the known positions using the WKB expression that integrates the refractive index profile. In Bottollier-Curtet's method, a trapezoidal integration is used over the entire propagation path. Since the result turned out unstable, a stabilization mechanism was introduced [3]. Each phase-shift is averaged with the previous step. In order to improve the accuracy of the reconstructed profile, new shapes were investigated for the last integration step. The purpose is to determine which is the best method that eliminates the need for a stabilization factor, has a more accurate determination of the profile, and is more robust against noise and spurious events.

The first shape proposed to improve from the linear shape, was to use parabolas. The parabola is determined by assuming the boundary conditions of constant derivative, it ends with zero refractive index at the reflection point and the index value of up to two previous points. Therefore, a new parabola is found for each frequency step. Since the refractive index has a very steep derivative in the reflection point, the next shape investigated was a square root. In this case, no additional boundary conditions are assumed and the shape is the same during all reconstruction steps. The resulting method turned out to be equivalent to the suggestions in two references [4, 5] from different considerations. Lastly, by observing a refractive index profile in typical edge conditions, one can note how the shape is closer to a step function than a square root. Taking this into account, the next shape implemented was x^n with n position dependent. In latest generation tokamaks operating at H mode, a linear fit of n from zero at the edge to 1/2 at the pedestal position represents well the correct shapes.

A comparison of the error profile of all methods is done in Fig.1. The test profile was of typical latest generation tokamaks in H mode with a pedestal at the 16 cm position. The use of parabolas obtained the same order of magnitude of accuracy as the linear shape. However, no stabilization factor was necessary. The square root shape showed much improvement in the core region accuracy, but almost negligible improvement in the edge. Lastly, the use of the profile adapted shapes improved the edge accuracy of an order of magnitude. In addition, when all methods were tested against the increase of white noise in the phase measurement, the edge region with adapted index shapes was less sensitive, and the error increased less. Using the adapted shapes is even more crucial if the amount of probing frequencies is reduced to decrease the reconstruction time in real time applications. In such cases, adapting the shapes reduces the decrease in the reconstruction accuracy.

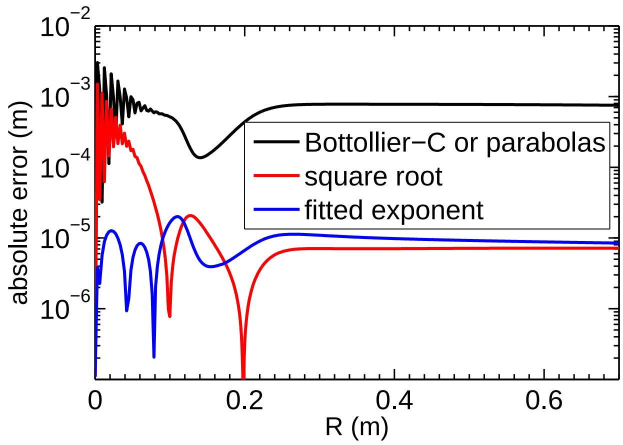

Figure 1: *Absolute error profiles for all methods with 500 frequency points on a typical H mode profile of latest generation tokamaks.*

Ideally, the shape adaptation could be locally determined without previous information of the density profile shape. Thus, being able to still use the best integration shapes if there is any change in the profile shape or the method is to be used in other machines with different parameters. While investigating the ideal exponent n for all positions, it was observed that as the integration step is larger, the exponent goes to zero, or the shape goes to a step function, with the speed depending on local parameters. A new shape that take this into account is under investigation, and although it showed possible to reconnect the local plasma parameters to the best exponent n, a full mapping along the full range of parameters is still underway.

Reconstruction of blind regions

Some events during a discharge, e.g. gas puffing, pellet injections and MHD events, can introduce hollow areas in the cutoff profile that cannot be probed directly. Although, the time of flight signal will contain a signature that is related to the perturbation properties. This was verified by plotting the phase-shift jump, calculated with the WKB expression, versus the depth of the density valley. The resulting relation is well fitted with a polynomial, and was successfully implemented to recreate holes that were introduced in the density profile. Nevertheless, this relation varies with the local plasma properties and the perturbation width. Furthermore, in such situations there are time-dependent full wave effects to take into account in the observed signals. Therefore, the WKB approximation is not suitable to describe all phenomena and 1D Full-Wave simulations are being used to recreate these signals. Furthermore, the time-dependent effects are also affected by the frequency sweeping rate implemented. This effect can appear in the signal magnitude and extension and must be corrected if the application sweeping rate is different from the simulated case.

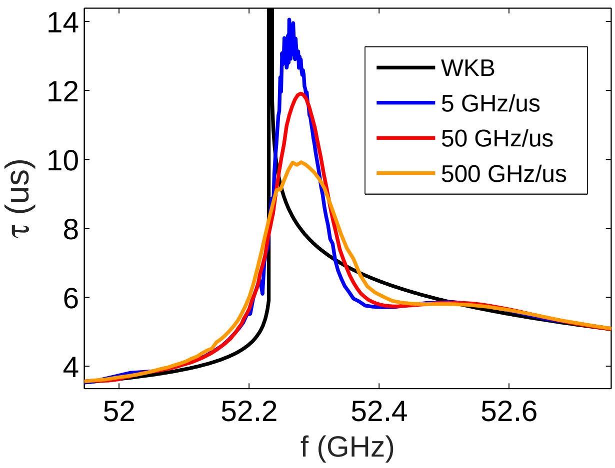

Figure 2: *Signature of a gaussian hole perturbation in the WKB and Full-Wave time of flight signals.*

In Fig.2, the signature of a hole perturbation is compared between the WKB solution and the Full-Wave code for different sweeping rates. The WKB signal has a sharp jump in the time of flight and a quick decay follows. On the other hand, the Full-Wave signal presents a smoother peak. The rise in the time of flight before the jump is assumed to be due to the tunneling effect into the valley, and the fluctuations after, due to the interference of the waves temporarily trapped inside the valley. In Fig.3, holes of different depths are plotted. The height of the time of flight peak in the full wave signal is not anymore a good indicator of the hole depth, as it was in the WKB signal, due to the interference processes which are stronger in that region. However, the decay after the

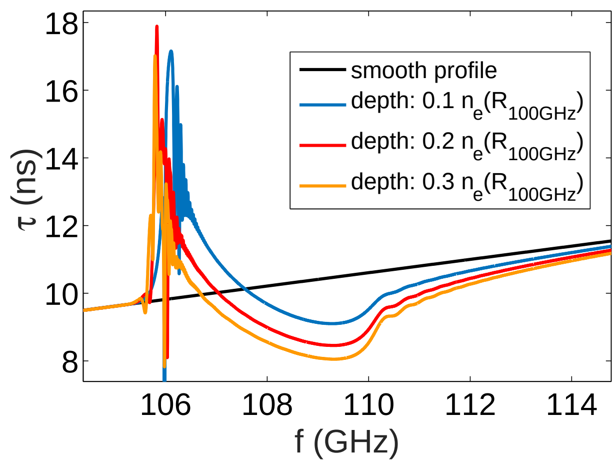

Figure 3: *Signature of a sine-shape hole perturbation in the Full-Wave time of flight.*

peak is shifted between the different depths and it can be used as an estimator for the perturbation depth. In addition, the minimum in the signal is connected to the inflection position of the density profile, suggesting a good indicator for end of the perturbation. This is the simplest example and additional cases are also under investigation, such as bumps and a combination of both cases. Similar features are present for all signatures and are being explored to determine relations that in the end will make possible to estimate the shape and size of these perturbations from their signatures in the time of flight measurements.

Conclusions and future prospects

The new method of adapted x^n shapes improved the accuracy in the edge region of an order of magnitude compared to the square root or the existing methods presented. The regions that are adapted to lower values of n also were less sensitive to the introduction of white noise in the phase-shift signal. For real-time applications it is even more crucial to implement this adaptation if the number of probing frequencies is reduced, since the bigger is the spatial step, the closer the exponent n is to zero. The profile of the best values for n was explained for an example case, but a general relation to any plasma shape, based on the local plasma properties, was checked to be possible and is underway.

The estimation of the size of density perturbations that create blind regions was shown possible in the scope of the WKB phase-shift signal. In the scope of 1D Full-Wave simulations, some features in the time of flight signal were identified to be connected to the size of the perturbation under investigation. The near future goal is to obtain these relations and be able to estimate the perturbation shape and size from its signature in the time of flight signal.

With the previous two subjects finalized, the next step to improve the profile accuracy will be to access the current technique to initialize the profile reconstruction. Some observed cases seem to have a shifted density profile and this feature has been checked and can be demonstrated to be typical of mistakes in the initialization.

Acknowledgement

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