FULL-SIZE SIMULATIONS OF A FLUCTUATION REFLECTOMETER IN TOKAMAK PLASMAS

M. Colin, S. Heuraux, G. Leclert[†], F. Clairet[‡], R. Sabot[‡] and S. Hacquin[&]

LPMI, Unité CNRS 7040, Université Henri Poincaré Nancy I
BP 239, 54506 Vandoeuvre Cedex - France

[†] *LPIIM, Unité CNRS 6633, Université de Provence, Centre St-Jérôme*
Case 321, 13397 Marseille Cedex 20 -France

[‡] *Association Euratom-CEA pour la fusion contrôlée, CEA Cadarache*
13108 St Paul-lez-Durance – France

[&] *Centro de Fusão Nuclear – Associação EURATOM / IST, Instituto Superior Técnico,*
Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Introduction

The X-mode reflectometer is a useful tool to provide the edge density profile and it can also give information on the plasma fluctuations. Presently, the data on plasma fluctuations are used as a qualitative information, but it is now necessary to obtain quantitative information about the density fluctuations, either plasma turbulence or MHD-like (quasi-coherent) events. To reach this goal, full-size simulations of O and X-mode heterodyne reflectometers have been performed to find the signature of different kinds of density perturbations. In this study, we have ignored the magnetic field perturbations in the case of the X-mode reflectometer because it has been shown that magnetic field perturbations can be neglected except for a probing frequency close to the electron cyclotron frequency [1] for typical tokamak parameters. As it has been put forward in the paper of Y. Lin *et al*[2], 1D simulations still remain useful and necessary to understand the numerous physical processes involved in tokamak plasmas. Reflectometer simulations with typical Tore Supra tokamak parameters have been performed. They exhibit a wide range of responses depending on the different types of fluctuations. However the simulation parameters must be chosen with some care. When the sweep rate is too short as currently found in simulations to save computation time, spurious physical effects are introduced and the time variations of the reflectometer measurements do not correspond to an experimental situation as shown in this paper. These results have been obtained after an improvement of the simulation of the reflectometer detection system by using an equivalent description of the heterodyne system (named IQ in the following) which gives the phase and amplitude at each frequency. We also use other classical methods (sliding FFT and so on) to determine the time of flight.

Sweep rate effects

We first show how a sweep rate artificially too high can introduce distortions of the signal scattered by a given density perturbation. The simulations are done for a fixed tokamak plasma configuration corresponding to the Tore Supra parameters. The first spurious effect is on the time of flight measurement. To avoid the spurious effects presented here, the choice of the sweep rate should be done carefully. The figures 1a-b exhibit the changes seen for a plateau density perturbation with an amplitude of 5 % of the unperturbed density and a width of 3 cm centered at 15 cm from the edge. For a high sweep rate (1000 GHz/µs) the sliding FFT signal is smoothed and spread whereas a low sweep rate (100 GHz/µs) the sliding FFT signal becomes sharper and shows higher time of flight variation amplitudes. For the IQ method, the time of flight deduced from the phase versus probing frequency shows the same behavior than the sliding FFT. We have also some information on the phase oscillation due to a frequency mixing. This oscillation zone becomes sharper when the swept frequency rate decreases. A second effect is on the signal amplitude. It results in a decrease of the reflected wave amplitude when the frequency corresponds to the flat (top) part of the density perturbation (plateau). At this moment, the energy flux near the cut-off frequency is slower than the energy flux at higher frequency and as the energy flux is conservative the amplitude is reduced when it comes back in vacuum. This amplitude variation increases with the sweep rate. A sweep rate below 10 GHz/µs guarantees that these effects do not occur. However, a good compromise between the computation time and the accuracy of the description is obtained with a sweep rate of the order of 100 GHz/µs. These computations correspond to 1.5 million of time steps and 10 thousands of spatial steps for a full-size simulation of the X-mode Tore Supra reflectometer (50 –75 GHz) with a relative accuracy of 10^{-4} on the time of flight.

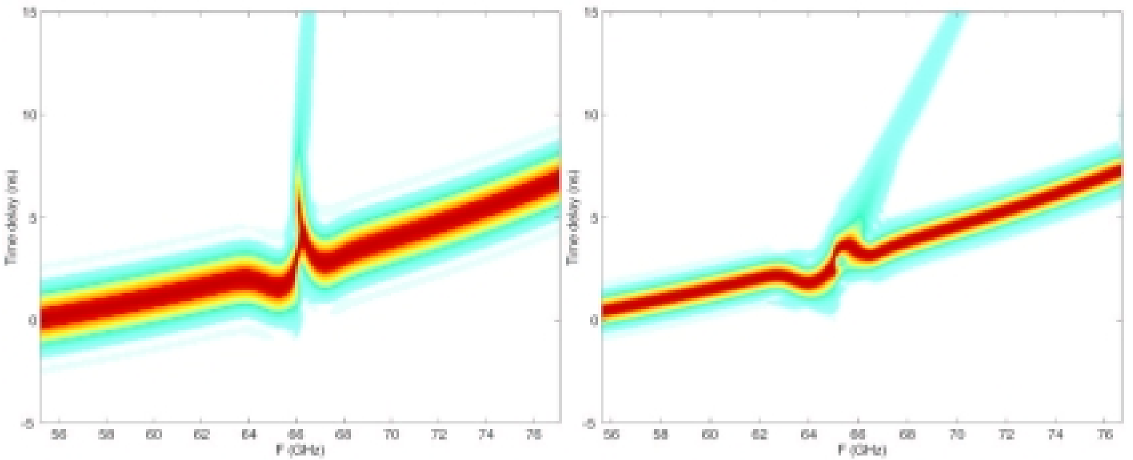

Fig.1: X-mode Time of flight for two sweep rates 100 GHz/µs (left) and 1000 GHz/µs (right)

Coherent density perturbation effects versus shape, width, position and amplitude.

MHD-like perturbations in the form of a density plateau in typical Tore Supra plasma have been considered. Figure 2 displays the case of a plateau, 3 cm wide, with sharp edges ($n_e(x_f)$ = constant, x_f the center position of the plateau) and a sweep rate of the order of 300 GHz/µs, which introduces some small distortions without effect on the given interpretations. The corresponding time of flight variations can be interpreted as follows :

- decreases of the time of flight are due to the density wall and can be evaluated by using a simple model of mirror with the same plasma between the reflectometer and the wall,
- increases of the time of flight are related to the propagation of the probing wave which is slowed down across the plateau. However, for the X-mode, due to the inhomogeneous magnetic field, a density plateau does not correspond to a refractive index plateau which would give the highest value of the time of flight jump.

For a density plateau with smooth edges, the reduction of the time of flight is possible only if the local density gradient is greater than a threshold depending of the plasma profile. Other shapes of the density perturbation follow the same rules. Generally, for a perturbation with the sequence wall-plateau, corresponding to steepening of the density gradient (ITB-like profile), the time of flight perturbation presents the sequence hole-hill.

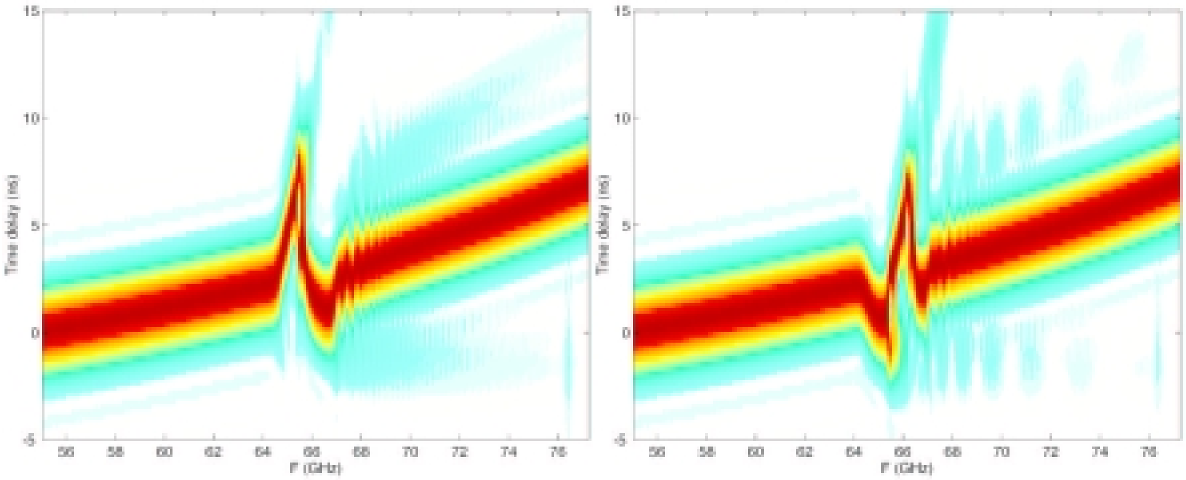

Fig. 2: Time of flight versus frequency for 2 cases : density plateau followed by density wall (left) and sequence density wall-plateau-wall (right) with the same plateau width (3 cm)..

When the plateau moves inward the plasma, the frequency size of the shape of time flight decreases. The reason is obvious, the needed range of frequency to go through the perturbation decreases when the position is closer to the tokamak plasma center.

For a fixed position (x_f=15 cm) of a plateau density perturbation, the X-mode reflectometer shows significant variations of the time of flight only for the plateau width greater than 0.5 cm. This limit is higher for a density plateau with smooth edges.

For a Gaussian density perturbation, the time of flight begins to increase with the perturbation amplitude, but then the refractive index can form a plateau, resulting in a strong increase of the time of flight (depending on the plateau width). At even higher amplitude a density hole occurs that reduces the increase of the time of flight and eventually there remains only the decrease of the time of flight. A number of other cases of coherent perturbation have been computed to verify these features.

Broad spectrum density fluctuations

We have studied more specifically to the case of broad spectrum fluctuations with typical tokamak spectrum [3] ($S(k)$= Cte for $k<k_{lim}$ and $S(k) \propto k^{-3}$ for $k>k_{lim}$). The simulations and an experiment [4] seems to show that the k-spectrum profile exhibits a maximum around k_{lim}= 0.5-1 cm^{-1} in the radial direction. Figure 3 shows the role of the limit value k_{lim} on the reflectometry signal with this turbulence spectrum. The value of k_{lim} determines the modulation of the reflectometer signal : at moderate amplitude (1%) the smaller the value k_{lim}, the higher the characteristic wavelength of the modulation.

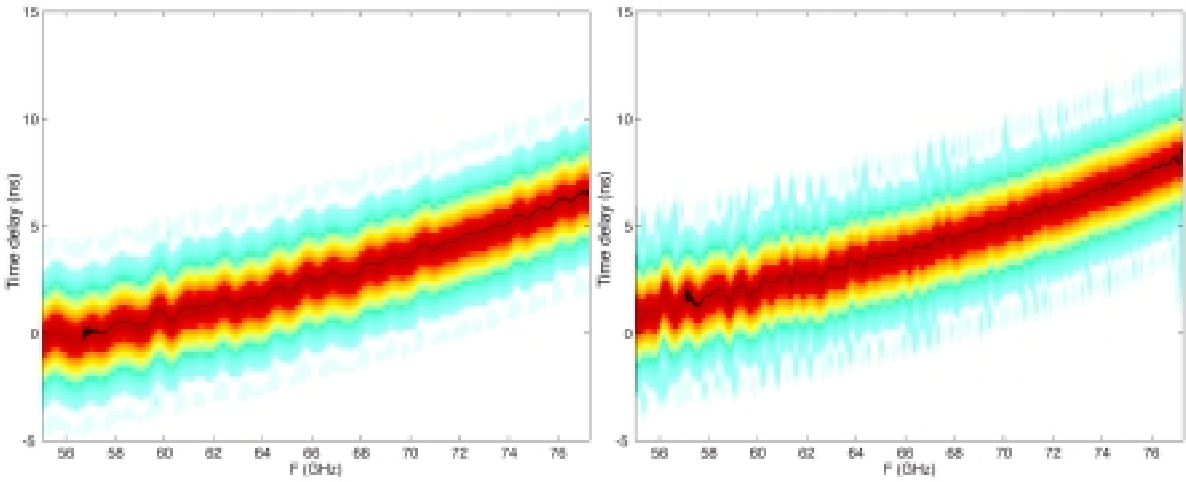

Fig. 3: Time of flight variations versus frequency for broad k-spectrum with different k-wavenumber limits klim=4 cm^{-1} (left) and 10 cm^{-1} (right) including the IQ method (black line).

At higher amplitude (10 %) of the density fluctuations, structures like those discussed in the previous section occur randomly and strongly distort locally the time of flight evolution. That is to say, locally the probing wave seems to see, for example, an equivalent sequence wall-plateau, then a broad spectrum with small amplitude follows by a wall-plateau-wall equivalent density perturbation and so on.

The behavior of a O-mode reflectometer leads approximately to the same conclusions in the case of the broad k-spectrum. However, the time of flight variations corresponding to the same density perturbation amplitude as for the X-mode case are lower.

References

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