A 2-D Code for the Analysis of Microwave Reflectometry Measurements in Fusion Experiments

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I - Introduction

In reflectometry experiments density fluctuations affect the propagation and reflection from a cut-off layer of electromagnetic waves. For a quantitative analysis of density fluctuations, 2-D effects (e.g. refraction and scattering) and the transverse field distribution of the microwave beam must be considered. The variation in the plasma parameters along the confining toroidal magnetic field can be neglected justifying a 2-D treatment. Several 2-D numerical codes (using finite difference methods) for the solution of the wave equation in plasmas have been recently developed /1/, /2/, /3/. Here we use a 2-D numerical code based on a spatially distributed RLC networks /4/ to model the full-wave equation in an inhomogenous plasma. The code is easily adapted to different antennae-plasma configurations and wave propagation in both O-mode and X-mode.

The code was applied to study the influence of poloidally propagating density fluctuations on reflectometry measurements at the W7-AS stellarator. A poloidal density modulation acts like a phase grating transferring part of the incident carrier into sidebands at different angles. A special feature of this experiment is the finite tilting angle of the symmetry axis of the transmitter/receiver antenna system versus the direction normal to the plasma surface. Therefore the reflected carrier and the sidebands are seen with different efficiency by the receiver antenna.

As observed experimentally, when there is asymmetry of the signal components, the numerical simulation reveals the existence of an anomalous drift of the phase ("phase runaway") above a given threshold value for the density fluctuation amplitude required.

II - Numerical code

The propagation of electromagnetic waves in an inhomogeneous medium can be described by an equivalent electric network consisting of inductance L, capacitance C and resistance R. The characteristics of the macroscopic density profiles and the small-scale fluctuations define the values of the network components./4/. If absorption processes in the plasma can be neglected the circuit reduces to a LC-network which, for the 2-D case, is shown schematically in Fig.1. The inductance in series is given by $L=\mu_0\Delta x$ and is kept constant. The spatial variation of the plasma parameters is contained in $\varepsilon(x)$ being the capacitance in parallel given by $C(x)=\varepsilon(x)\Delta x$, where Δx is the dimension of a plasma element with constant electron density n_e. In the calculations the grid size is $\Delta x\leq\lambda_0/12$.

The input impedance for every input node of the electrical network is calculated using matrix inversion programs. The transverse distribution of the input field is described by the input voltages (phase and amplitude). In analogy the individual return currents yield the transverse distribution (phase and amplitude) of the reflected filed.

The calculation has three basic steps: (i) Free-space propagating from transmitter antenna to plasma boundary. (ii) RLC-code for propagation and reflection in the plasma. (iii) Free-space propagation from plasma boundary to receiver antenna.

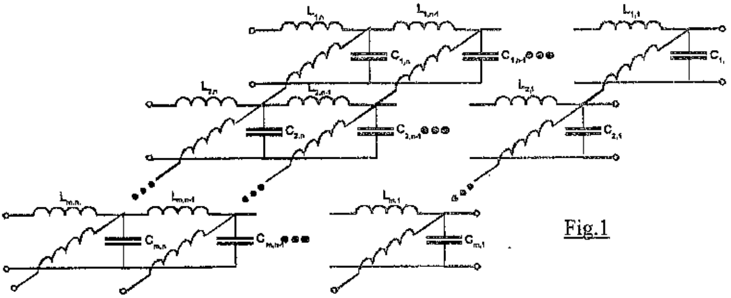

Fig.1

III - Phase runaway at the W7-AS reflectometry system

Depending on the operational range of the W7-AS stellarator a strong drift of the phase ϕ is observed ($d\phi/dt \sim 100 - 200$ kHz) which is usually referred to as "phase runaway". It is too large to be originated by a realistic radial movement of the cut-off layer. To explain it, poloidally propagating fluctuations have to be included and therefore 2-D calculations must be performed.

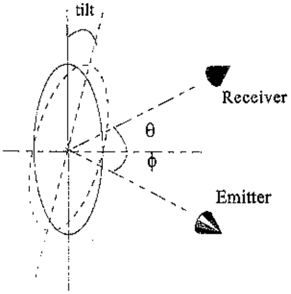

Fig.2

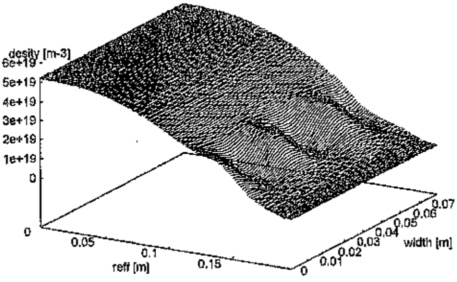

Fig.3

The reflectometry system installed at W7-AS /5/ operates with X-mode in the W-band (75-110) GHz. The two conical antennae use elliptical mirrors to produce a gaussian beam focused near the plasma edge. The antennas are oriented towards the torus axis and are separated by 12° with their symmetry axis in the equatorial plane. The plasma surface is not exactly perpendicular to the equatorial plane but is slightly tilted by 2.6°. In Fig.2 is shown schematically the antennae geometry considered in the 2-D simulation: tilt=2.6°, $\theta + \phi = 12°$. The radial density and magnetic field profiles represent typical operating conditions. Fig. 3 shows an example with $n_e(0)=5\times10^{19} m^{-3}$, and a periodic density modulation (with fixed amplitude and wavelength) propagating in the poloidal direction, radially localised around the reflecting layer (at $r_{eff} \sim 14$ cm, for f = 85 GHz).

Calculations are performed for every time step of the poloidally propagating fluctuation. The receiver antenna signal is characterised by its complex amplitude (real and imaginary part).

Fig.4 shows the evolution of the complex amplitude during one cycle of the perturbation, for increasing amplitude of the fluctuations and tilt=2.6^0. The threshold amplitude of the fluctuation for the onset of the phase runaway is 0.05 (normalised amplitude).

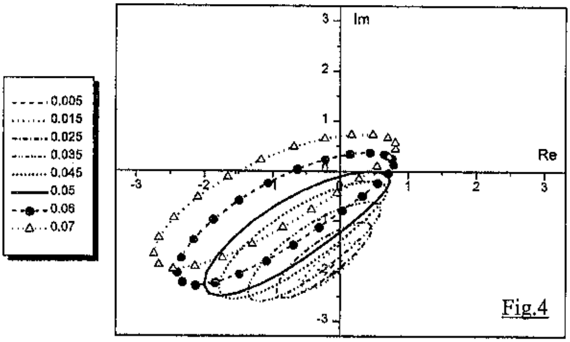

Fig.4

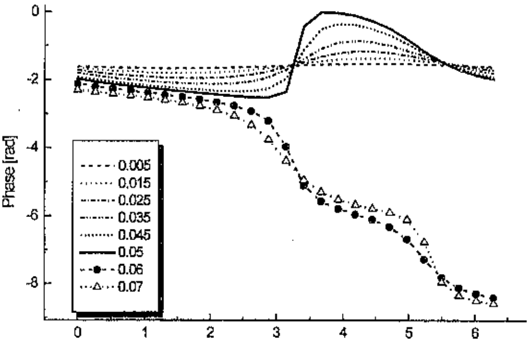

Fig.5

As can be seen from Fig.5, for small fluctuation amplitudes the output phase oscillates around its mean value. Once the threshold amplitude is reached, a jump of π in the phase occurs. As the amplitude increases further the phase continues to drift continuously in the same direction. In addition, the temporal behaviour of the signal amplitude (not shown here) is in agreement with experimental observations. The minimum of the amplitude occurs when the phase jumps by π due to destructive interference between signal carrier (ω) and sideband (ω±Δω(t)).

The frequency shift of the scattered sideband signal is $\Delta\omega = \bar{k}_{pol} \cdot \bar{v}_{pol}$, where $\bar{k}_{pol}$ is the poloidal wavevector and $\bar{v}_{pol}$ is the poloidal propagation velocity of the fluctuation. A good agreement with theoretical predictions is found /6/. As expected, no phase runaway is found when the tilt angle is set to zero.

In. Fig.6, as the amplitude of the density perturbation increases beyond the threshold (up to 0.11), the receiver output is dominated by the frequency shifted component. The phase changes continuously as $\phi(t)= \Delta\omega t$, that is, the signal obtained at the antenna output is Doppler shifted by Δω and therefore a drift of the phase with constant mean slope is detected by the reflectometer ("phase runaway").

The numerical results presented in Fig.6 predict that the mean slope of the phase drift reverses with the poloidal propagating velocity. Values of $d\phi/dt\sim\pm100$kHz are obtained, with $k_f = 2$ cm^{-1} , $V_{pol} \sim 3.2$ Km/s. This agrees with the results in the experiment where the inversion of the plasma poloidal rotation direction is accomplished by inverting the magnetic field.

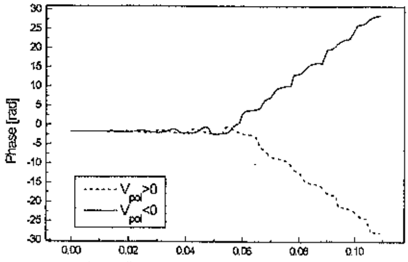

Fig.6

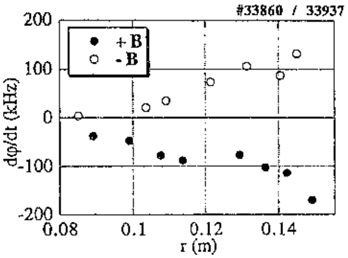

Fig.7

Fig. 7 shows the radial dependence of the phase drift measured at W7-AS for both signs of the magnetic field. For these experiments a direct comparison of the phase runaway (and the deduced poloidal propagation velocity) with spectroscopy measurements of the plasma rotation could be made /7/. The simulation results shown in Fig.6 fit the two symmetric experimental points obtained at $r_{eff}\sim 0.14$m shown in Fig.7.

IV- Concluding Remarks

A 2-D code based on spatially distributed RLC networks has been used to model the propagation of electromagnetic waves in a plasma with density fluctuations.

The code was applied to the study of poloidally rotating periodic structures in X-mode reflectometry experiments at the W7-AS stellarator. Good agreement with experimental results was found. The finite tilt angle of 2.6^0 from the vertical direction was identified as the necessary condition for the observed phase runaway. It could be shown that there exists a threshold value for the amplitude of the density fluctuation needed to observe the runaway phenomenon. The experiments performed with the reflectometer have showned that this value can easily be surpassed by the density turbulence in the L-mode or during ELMs.

Acknowledgments

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