J. Plasma Physics (2006), *vol.* 72, *part* 6, *pp.* 1205–1208. © 2006 Cambridge University Press
doi:10.1017/S0022377806005940 Printed in the United Kingdom

Developments on reflectometry simulations for fusion plasmas: application to ITER position reflectometers

FILIPE DA SILVA[1], STÉPHANE HEURAUX[2] and MARIA MANSO[1]

[1]Associação EURATOM/IST–Centro de Fusão Nuclear, Instituto Superior Técnico, 1046-001 Lisboa, Portugal

[2]Applications, Unité du CNRS 7040, Université Henri Poincaré, Nancy 1, BP 239, 54506 Vandœuvre Cedex, France

(Received 23 July 2005 and accepted 19 December 2005)

Abstract. To improve the understanding of reflectometry diagnostics, simulations of full reflectometer systems are needed and should include: (i) wave propagation; (ii) proper antenna setup and signal injection technique; (iii) signal detection and signal processing techniques; and (iv) real size of the system. Simulation of wide band frequency modulated reflectometry where the frequency is continuously swept adds further requirements. A good plasma description is also vital. In this work we apply this concept of full reflectometer simulation to the ITER position reflectometer taking into account the technological constraints.

1. Introduction

Microwave reflectometry is a technique used to diagnose fusion plasmas to obtain information on the electronic density such as the density radial profile or information on coherent plasma events such as magnetohydrodynamic activities and/or relaxation and turbulent phenomena [1]. To improve the understanding of the diagnostic, simulations of full reflectometer systems are needed including: (i) wave propagation in a fluctuating plasma; (ii) proper antenna setup and signal injection technique; (iii) signal detection and signal processing techniques; and (iv) real size of the system (its design). Simulation of wide band frequency modulated reflectometry (frequency modulated continuous wave – FMCW) where the frequency is continuously swept adds further requirements since a good behavior throughout the wide frequency band is required, including the numeric scheme used, absorbing boundary conditions, and signal injection (source). Signal injection poses particular challenges in our case where a monostatic setup is used (one single antenna used both for emission and reception) with the signal continously injected on the system while being simultaneously received.

2. Code description

The code developed is a two-dimensional (2D) finite-difference time domain (FDTD) full-wave Maxwell code. Considering a transversal magnetic (TM) propagation

https://doi.org/10.1017/S0022377806005940 Published online by Cambridge University Press

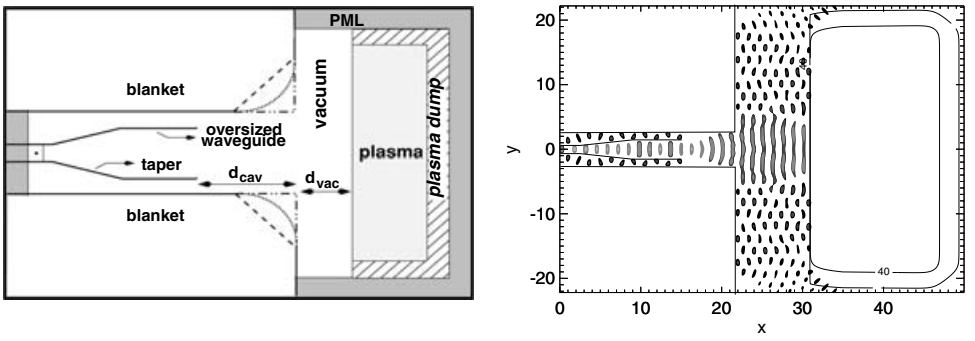


Figure 1. (a) Schema of the simulation layout which reflects the physical setup of the position reflectometer planned for ITER (b) with three proposed blanket openings (squared, slanted, and rounded). The electric field contour using the squared blanket is shown. In *plasma dump region* the plasma is decreased to a null density (hyperbolic tangent) to match the vacuum propagation conditions suited to the PML technique.

(E_z, B_x, B_y) and using a FDTD Yee scheme [2] we obtain the kernel for the O-mode reflectometry code. The equation for the current density couples the plasma model to the wave electromagnetic field [3, 4]. A perfectly matched layer (PML) is used as a boundary condition [5]. The signal excitation on the code is quite flexible: it allows the excitation of a chosen waveguide mode (usually TE_{10}) with the desired waveform source (Gaussian pulse, amplitude modulated, fixed frequency, frequency modulated or any arbritrary waveform). The code usually runs with a monostatic antenna setup (it is possible to use an arbitrary number of antennas in emission and/or reception). An achievement of the code was the implementation of a unidirectional transparent source (UTS) unidirectional injection of the probing wave (towards the plasma) while receiving the reflection separated from the source excitation [4]. The plasma is modeled through the definition of the electronic density $n_e(\mathbf{r}, t)$, which is coupled to the equations of electromagnetic propagation by the numeric scheme. The density $n_e(\mathbf{r}, t)$ is, in general, a function of space and time since the code allows time evolution of the density profile due to modifications of the base plasma on time, coherent plasma modes and turbulence. Turbulence follows the model proposed in [6] with the density perturbation at each point modeled as a sum of modes with random phase and amplitudes chosen in agreement with experimental data. The code can also accept turbulence given by an external source (turbulence code). In Fig. 1(a) a schema of the simulation layout for the ITER position reflectometer is shown. The signal detected in the waveguide (in the code grid) corresponds to a high-frequency signal (in the gigahertz range) which we do not access experimentally. On reflectometry these signals are down converted to base band before being digitized. To fully simulate a reflectometer response, the processing of the code results includes homodyne detection (in-phase and quadrature detection or single ended). This allows us to recover reflectometry signals similar to experimental values which reflect the problems encountered by the experimentalist. The usual signal processing techniques can be applied to these signals. This permits not only a full reflectometer simulation but the use of the code as a tool for testing and validating new techniques of signal analysis. We have used several techniques such as maxima detection, *In-phase/Quadrature* (I/Q) detection, sliding fast

https://doi.org/10.1017/S0022377806005940 Published online by Cambridge University Press

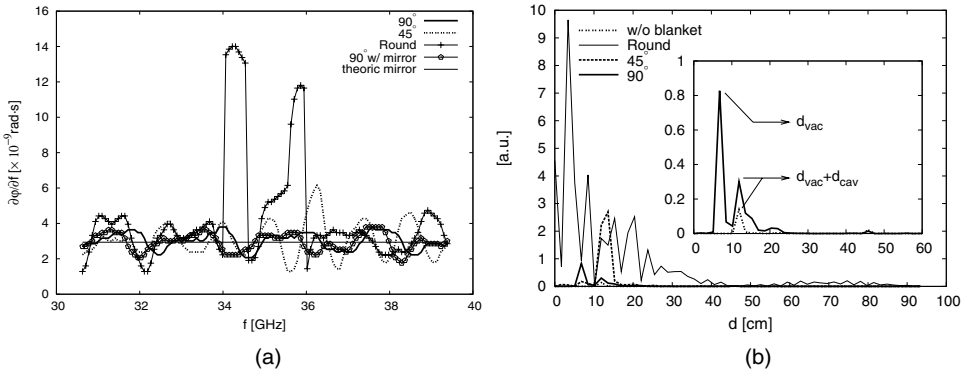


Figure 2. (a) The phase derivatives for simulation using the three blanket openings, squared (90G), slanted (45G), and rounded (Rnd) with the ITER plasma and a mirror (90G). (b) The spurious reflections signatures are identified.

Fourier transform (FFT) together with some complex experimental techniques such as burst-mode and best-path (Floyd's algorithm) [7].

3. Application to ITER

This application of the code to the ITER position reflectometer illustrates many of the aspects discussed above. It is important to consider the geometric aspects of the reflectometer full-size setup which will influence its response: use of oversized waveguides, open waveguide as emission/reception antenna, existence of a surrounding blanket structure forming a cavity around the mouth of the waveguide, proximity of a very steep plasma, the need for a good signal injection – use of the UTS together with a tapered injection allows the excitation of a broad band frequency modulated signal without the generation of spurious modes and a decoupling of the reflected signal from the probing signal. The simulation layout reflecting the physical setup planned for the ITER position reflectometer is schematized in Fig. 1(a). Three possible openings for the blanket are simulated, squared (90°), slanted (45°), and rounded and the results compared. The probing wave is FMCW swept from 30 to 40 GHz. The plasma increases linearly at the edge, the region being probed in these simulations, being extremely steep with a density gradient value of $L = (\Delta n_e/\Delta x_c)|_{40\,\mathrm{GHz}} = 1 \times 10^{24}\ \mathrm{m}^{-4}$, that is, for 40 GHz the cut-off position is reached in a distance of $\lambda_{40\,\mathrm{GHz}}/20$. In Fig. 1(b) the electric field contour snapshot of a frequency sweep is shown for the case of the squared blanket. The reflectometry signal resulting from an homodyne detection (of the reflected signal detected at the waveguide) was FFT analyzed and, from the frequency distribution matrix, the beat frequency f_B was obtained and consequently the phase derivative $\partial\varphi/\partial f = 2\pi(\partial f/\partial t)^{-1} f_B$ was calculated, with $(\partial f/\partial t)^{-1}$ the sweeping rate. In Fig. 2(a) we show the phase derivatives for the three blanket configurations (squared (90G), slanted (45G), and rounded (Rnd)), together with the phase derivative due to a metallic mirror placed at the plasma initial position (with the squared blanket). The constant phase derivative due to a perfect mirror is also presented as a reference. These results indicate that the ITER plasma induces a mirror-like gradient reflection. Comparing, for the squared blanket, the phase derivatives due to the plasma and mirror reflections, the same behavior is observed. This mirror behavior of the

https://doi.org/10.1017/S0022377806005940 Published online by Cambridge University Press

plasma can also be observed in Fig. 1(b) where the wave barely enters the plasma penetrating only a fraction of a wavelength being *specularly* reflected. This is not an artifact since the code is able to describe metallic and metallic-like reflections. The results obtained with the three blanket types present, of course, this specular behavior differing on the spurious multi-reflection effects induced by the blanket structure which account for the wavering of the phase derivatives around the ideal response of a mirror. With the change of variable $f \mapsto 2f/c$ (c is the speed of light) and doing a FFT on the $\partial\varphi/\partial f(2f/c)$ signals, we obtain functions $\Phi(x)$ with the information on the distances involved on the spurious multi-reflections. Fig. 2(b) shows these distance marks. In the inset $\Phi(x)$ is shown with the squared blanket and without the blanket. The two distance signatures (90G) can be identified with the distances blanket–plasma (d_{vac}) and antenna–plasma ($d_{\mathrm{vac}} + d_{\mathrm{cav}}$). Without the blanket structure there is a minute reflection between the antenna and the plasma but it can be neglected. The amplitudes of the spurious multi-reflection contributions to the phase derivative indicate that the squared blanket is the best of the three.

4. Discussion

ITER plasma, due to its extreme gradient at the edge, acts as a specular reflector. This will allow only the location of the plasma initial position. However, since the reflectometer in question is intended to be a position in the plasma, this is not a major drawback. Due also to the steep gradient, the location of this single point is extremely resistant to the influence of turbulence (up to $\delta n_{\mathrm{e}}/n_{\mathrm{e}}|_{35\,\mathrm{GHz}} = 50\%$ rest mean squared), no visible modification was observed). Only bulk movements of the plasma will influence the determination of the first point. Simulations have also shown that the main spurious effect on the phase derivative is caused by the multi-reflections due to the blanket. Among the three geometries tested, the squared blanket is the one offering the lowest level of reflections able to satisfy the spatial position resolution criterion.

Acknowledgements

This work has been carried out in the framework of the Contract of Association between the European Atomic Energy Community and Instituto Superior Técnico (IST) and of the Contract of Associated Laboratory between Fundação para a Ciência e Tecnologia (FCT) and IST. The content of the publication is the sole responsibility of the authors and it does not necessarily represent the views of the Commission of the European Union or FCT or their services.

References

[1] Sabot, R. et al. 2004 *Int. J. Infrared Millimeter Waves* **25**, 229–246.
[2] Yee, K. S. 1966 *IEEE Trans. Antennas Propagat.* **14**, 302–307.
[3] da Silva, F. et al. 2001 *Rev. Sci. Instrum.* **72**, 311–314.
[4] da Silva, F. et al. 2005 *J. Comput. Phys.* **203**, 467–492.
[5] Berenger, J.-P. 1994 *J. Comput. Phys.* **114**, 185–200.
[6] Heuraux, S. et al. 2003 *Rev. Sci. Instrum.* **74**, 1501–1505.
[7] Varela, P. et al. 1999 *Rev. Sci. Instrum.* **70**, 1060–1063.

https://doi.org/10.1017/S0022377806005940 Published online by Cambridge University Press