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Titre: Développement d'un code de réflectométrie "full-wave" 3D européen

Title: **Development of a European 3D full-wave reflectometer simulation code**

S. Hacquin[1], E. Blanco[2], G. D. Conway[3], S. Heuraux[4], C. Lechte[5], F. da Silva[6], A. Sirinelli[7]
and ITM-TF contributors*

[1]Association EURATOM-CEA, CEA/DSM/IRFM, Cadarache 13108 Saint Paul Lez Durance, France
[2]Laboratorio Nacional de Fusion, Asociacion EURATOM-CIEMAT, Madrid, Spain
[3]Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, D-85748 Garching, Germany
[4]Université de Lorraine, IJL, UMR 7198, BP 70239, Vandoeuvre , F-54506 Cedex, France
[5]Institute of Interfacial Process Engineering and Plasma Technology, Univ. of Stuttgart, 70569 Stuttgart, Germany
[6]Associação EURATOM/IST, IPFN, Av Rovisco Pais, 1049-001 Lisboa, Portugal
[7]Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
** See the Appendix to the paper of G. Falchetto et al., Nucl. Fus. submitted (http://www.efda-itm.eu)*

Mots-clefs: Plasmas de fusion – Diagnostics micro-ondes – Réflectométrie – Simulation numérique

Keywords: Fusion plasmas – Microwave diagnostics – Reflectometry – Numerical simulation

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Résumé

La réflectométrie micro-onde est un diagnostic polyvalent utilisé dans la plupart des machines à fusion pour la mesure du profil de densité électronique, des caractéristiques de la turbulence du plasma et de sa vitesse de rotation. L'interprétation des données de ce diagnostic reste cependant délicate en raison de la complexité des phénomènes physiques gouvernant la propagation de l'onde sonde dans les plasmas de fusion turbulents. Les simulations de réflectométrie ont connu un intérêt croissant dans les dernières décennies, conduisant à une meilleure compréhension des interactions onde-plasma et à une interprétation plus aisée des mesures de réflectométrie. Un consortium européen de physiciens travaille depuis quelques années au développement d'un code de réflectométrie "full-wave" 3D. Prenant en compte toutes les hypothèses physiques pertinentes pour simuler la propagation d'ondes dans des milieux dispersifs, ce code européen est un outil innovant. Originellement destiné à l'étude des diagnostics micro-onde, il offre également d'autres applications potentielles: simulation du chauffage cyclotron électronique, conception de composants micro-ondes, …

Abstract

Reflectometry is a versatile microwave diagnostic, which is used in most of the existing fusion devices for measurement of the electron density profile, of the plasma turbulence properties and of the plasma rotation velocity. However the complexity of the physical processes taking place during the propagation of the probing wave in turbulent fusion plasmas makes the interpretation of reflectometry data somewhat tricky. Reflectometry simulation activities have known an increasing interest in the last few decades; leading to better understanding of the wave-plasma interaction processes and enhanced interpretation of the reflectometer data. A European consortium of physicists has been working for the last few years to the development of a new 3D full-wave reflectometer simulation code. Including all the necessary physics features for relevant simulation of the wave propagation in dispersive media this European code is a promising tool. Primarily devoted to supporting the operation and the design of microwave diagnostics it also offers other potential applications: electron cyclotron heating simulation, design of microwave components …

Introduction

Successful operation of thermonuclear fusion devices requires the use of a large number of diagnostics to characterise the plasma and the plasma-facing components [1-2]. Such diagnostics are essential to ensure the machine protection and efficiently control the plasma as fast data processing techniques now allow real-time measurement of key plasma parameters [3]. Moreover post-discharge analyses of the diagnostic data are valuable for physics studies and better comprehension of the behaviour of fusion plasmas [4]. Synthetic diagnostics play a major role in many fields of plasma physics and fusion science. They help in understanding the diagnostic response (and thus in designing better diagnostics) as well as in the interpretation of experimental results (which is crucial to the correct understanding of the physical processes occurring in fusion plasmas) and in the validation of theoretical models (via comparison of simulated and experimental data). Reflectometry is a versatile diagnostic technique which is widely used in fusion experiments, mainly for the measurement of density profile and fluctuations (linked to several kinds of plasma instabilities and turbulence) [5]. The last two decades have seen the development of a large number of "full-wave" reflectometry codes, which rely on numerically solving Maxwell's curl equations in the presence of a plasma permittivity tensor. For computational reasons most of these full-wave codes were restricted to 2D geometry [6-10]. However, the continuing progress in processors speed has recently opened the way to the development of 3D full-wave reflectometry codes, as for example the one currently being developed by a European consortium of researchers in the frame of the Integrated Tokamak Modelling Task Force (ITM-TF*) activities of the EFDA (European Fusion Development Agreement) programme [11]. The paper is organised as follows. In section 1 the basics of thermonuclear fusion and of plasma diagnostics, with special emphasis on microwave reflectometry, are briefly reminded. The motivations for a reflectometry simulation code are discussed. Then the description of the European 3D reflectometry code is given in section 2 while preliminary results and critical issues are discussed in section 3. Some perspectives of this work are presented in section 4.

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1. Diagnostics for fusion plasmas and motivations for a reflectometry simulation code

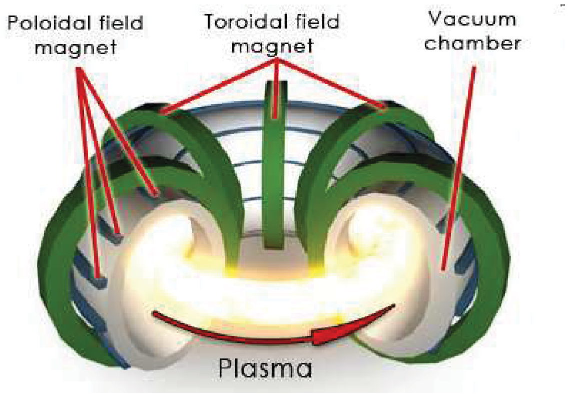

Figure 1. Principle of magnetic confinement with a *tokamak* fusion reactor

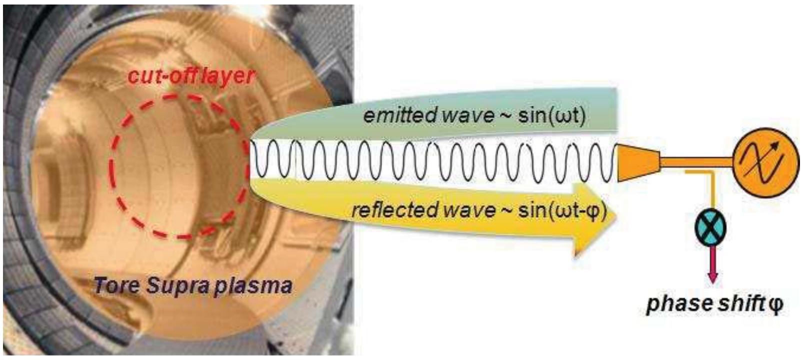

Figure 2. Principle of reflectometry measurement in fusion plasmas

Thermonuclear fusion of a deuterium (D) nucleus and a tritium (T) nucleus (two isotopes of hydrogen) releases more than 17 MeV of energy, thus presenting a strong interest in the perspective of developing fusion reactors for energy and electricity production. As the reaction rate is maximum in the 10-100 keV temperature range producing fusion energy requires a hot plasma (ionised gas) of D and T nuclei. It is also necessary that the product of the plasma density and the energy confinement time exceeds a certain level (so-called Lawson criterion) to ensure the plasma ignition. In order to fulfil this condition two ways of plasma confinement – inertial confinement and magnetic confinement - are under study. Inertial confinement consists in compressing a capsule of D-T with intense lasers while magnetic confinement relies on the use of magnetic fields to trap the charged particles of a fusion plasma [12]. Illustrated in Figure 1 the toroidal reactors called *tokamaks* are promising to achieve fusion energy via magnetic confinement [13]. A safe and efficient operation of a *tokamak* machine is only possible if most of the plasma parameters are accurately determined and controlled. A set of varied diagnostics (typically about 40) is then used for this purpose, allowing in particular (i) to preserve the machine from undesirable damages, (ii) to efficiently control the plasma for optimised performance and (iii) to provide useful data for physics studies and validation of theoretical models [1-4]. Based on the radar principle (as shown in Figure 2) a microwave reflectometer probes the plasma with electromagnetic waves in the 20 - 200 GHz frequency range. The probed plasma region depends on various parameters: the probing frequency, the plasma electron density and temperature, the confining magnetic field. It is widely used in fusion machines for studies of particles transport and plasma turbulence through measurement of the electron density profile (swept-frequency systems), the plasma fluctuations (fixed frequency systems) as well as the plasma rotation velocity (Doppler systems) [5]. Together with a variety of processes affecting the wave propagation (dispersion, diffraction, scattering, interferences, etc.) [14-15], the main difficulty in getting precise interpretation of reflectometry data comes from multidimensional effects which result from both plasma fluctuations in the transverse directions and divergence in the probing beam (imposed by the emitting and receiving antenna radiation patterns). This has motivated the development of full-wave reflectometry simulation codes devoted to a better understanding of the plasma-wave interactions and then an easier interpretation of experimental reflectometer data.

2. Description of the European 3D full-wave code

The European 3D reflectometry code relies on numerical computation of the Maxwell's curl equations given by:

$$\frac{\partial}{\partial t}E = \frac{1}{\varepsilon_0}\nabla \times H - \frac{1}{\varepsilon_0}J \tag{1}$$

$$\frac{\partial}{\partial t}H = -\frac{1}{\mu_0}\nabla \times E \tag{2}$$

The plasma response is taken into account through the equation of electron motion, which allows determining the plasma current vector J:

$$\frac{\partial}{\partial t}J = \varepsilon_0 \omega_{pe}^2 E - \omega_{ce} J \times B_0 \tag{3}$$

where B_0 is the applied magnetic field [14]. The square plasma frequency $\omega_{pe}{}^2$ and the electron cyclotron frequency ω_{ce} are linearly proportional to the electron density and the magnetic field, respectively.

A Finite Difference Time Domain (FDTD) iterative scheme is used to solve the three equations (1-3) on a Cartesian Yee grid [16-17]. The way how electric and magnetic field vector components are distributed on the Cartesian Yee grid is depicted in Figure 3. At least 20 grid points per wavelength is required to ensure accurate computations. The code is generic enough for any polarisation of the probing wave, thus allowing for simulation of O-mode (electric field of the probing wave parallel to the applied magnetic field) and X-mode (electric field of the probing wave perpendicular to the applied magnetic field) reflectometry. Synthetic antennas taking into account the radiation pattern of the emitting and receiving antennas are implemented into the code. A large variety of antennas, including for instance Gaussian beam ones, can then be modelled and either conventional or Doppler (oblique launch of the probing wave) reflectometry can be simulated. As the useful information inferred from a reflectometer comes from the reflected echo a directional coupler is used to discriminate it from the emitting probing wave. Similarly to reflectometer diagnostics a synthetic I/Q detector allows for separate evaluation of the amplitude and the phase of the reflected signal. In addition an absorbing Perfectly Matched Layer (PML) is implemented to avoid parasitic reflections on the grid boundaries [18]. More detail on the code description can be found in [6].

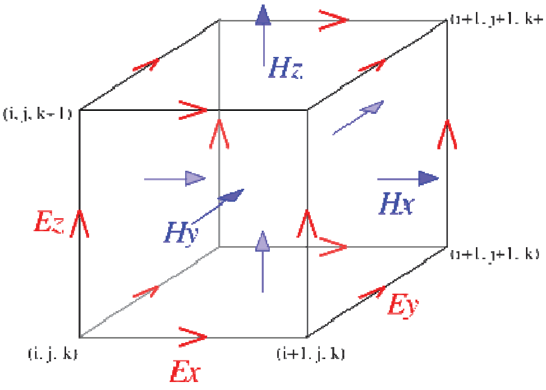

Figure 3. Illustration of a standard Cartesian Yee cell used in FDTD codes, showing how electric and magnetic field vector components are distributed

3. 3D simulation of reflectometry experiments

3.1. Preliminary results

In order to validate the code some simulations were carried out using realistic parameters as input. The code was first tested for O-mode polarisation of the probing wave, for which the wave propagation remains independent from the applied magnetic field. The simulations presented in the following were achieved for a grid size of 240 x 240 x 240 points and 20 points per wavelength using the following input parameters: a Gaussian probing beam wide of 4 mm and with frequency of 70.245 GHz. Moreover an electron density profile typical for tokamak plasmas (shown in Figure 4) was considered. The E_y electric field component in the 3D space computed by the reflectometry code is depicted in Figure 5. The probing wave is launched in the vacuum region (left side of the picture), propagates along the x-axis (as illustrated in Figure 4 the density increases towards the right direction) and then is reflected on the cut-off layer (defined for zero-value of the refractive index). Consequently the electric field represented in Figure 5 results from the mixing of the emitted and reflected waves. The 2D contour plots of the E_y electric field component on both the x-y and x-z planes (corresponding to plane cuts of the 3D representation in Figure 5) are shown in Figure 6. The electric field structure (with evanescent dropping of the wave amplitude behind the cut-off layer region) agrees with theoretical predictions, thus demonstrating the stability and the reliability of the code to model wave-plasma interactions.

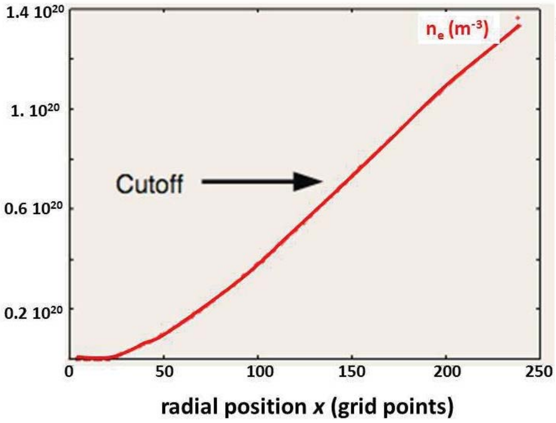

Figure 4. Example of typical density profile in a tokamak plasma used in 3D full-wave simulations

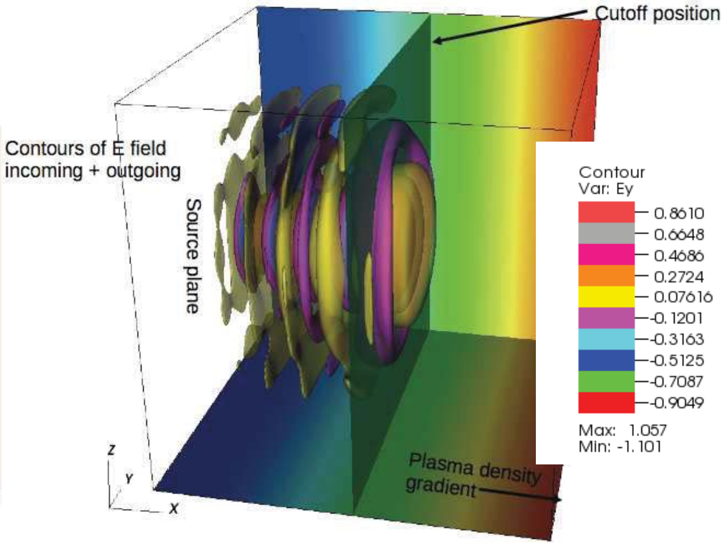

Figure 5. 3D contour plot of the *Ey* electric field component in O-mode reflectometry full-wave simulations.

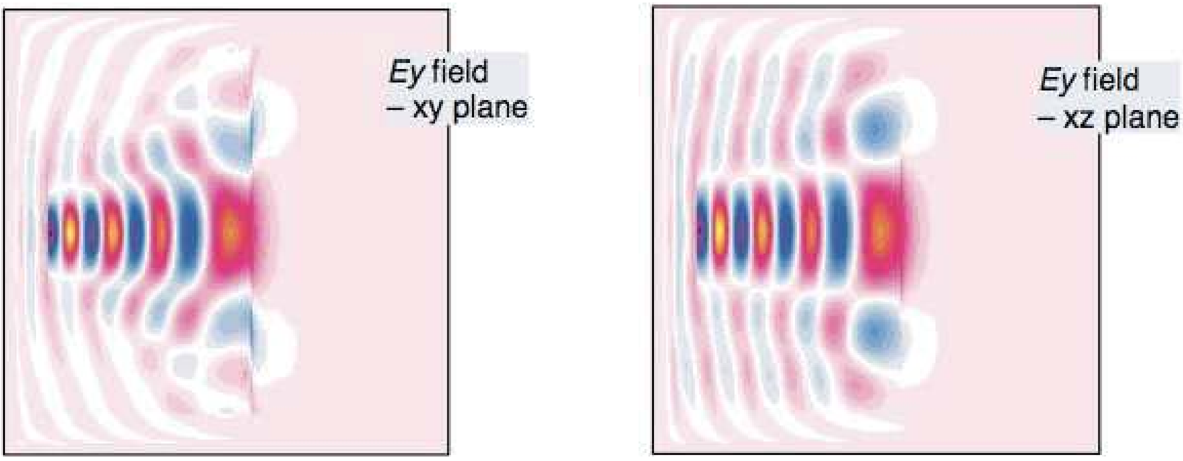

Figure 6. 2D contour plots of the *Ey* electric field component on both the *x*-*y* plane (left) and the *x*-*z* plane (right) obtained from O-mode reflectometry full-wave simulations [11]. The probing wave propagates along the *x*-axis (on which the density increases from the left towards the right) up to the cut-off reflecting layer.

3.2. Critical issues

As discussed in the previous section the European 3D reflectometry simulation code has been successfully tested on a regular Cartesian grid. However it should be noted that in its present configuration the use of the code is restricted to small grids (typically up to 10 - 20 wavelengths along each axis). The simulation of reflectometry experiments in large domains (as those required for application to large fusion devices, for instance ITER [19]) is not presently feasible since it would require too long computing time and too large memory for single-CPU computers. Further improvements are thus on-going to address this issue. First of all a mixed-scheme allowing for separate computation of the wave propagation in the vacuum region and in the plasma region, is being implemented. Indeed the computation of the wave propagation in the vacuum region can be carried out much faster using technics based on the Huygens' principle than from the J-solver that is required in the plasma region. Secondly the parallelisation of the code is under consideration as it is expected to bring a significant gain in the code speed.

4. Conclusion and perspectives

In the frame of the EFDA ITM-TF work programme a 3D full-wave reflectometry simulation code has been developed, adapted to the ITM data structure [20] and integrated in the EFDA ITM modelling infrastructure. It is a modularized code that offers a good level of flexibility: quick substitution of new elements as well as coupling to other codes, such as plasma turbulence gyrokinetic codes for instance. Although some efforts still have to be done to improve its speed it turns out to be a valuable tool for reflectometry data analysis and it is general enough for other potential applications: simulation of electron cyclotron heating in fusion plasmas, design of microwave components, etc.

Acknowledgments

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