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Study of wave propagation in various kinds of plasmas using adapted simulation methods, with illustrations on possible future applications

Étude de la propagation des ondes dans différents types de plasmas via différentes méthodes de simulation, avec des illustrations de futures applications potentielles

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ABSTRACT

The understanding of wave propagation in turbulent magnetized plasmas can be rather complex, particularly if they are inhomogeneous and time-dependent. Simulation can be a useful tool for wave propagation studies, provided that the "model" equations take into account the characteristics of the medium relevant for the studied problem and that the numerical scheme including boundary conditions is stable and accurate enough. The choices for the model equations and the corresponding schemes are analyzed and discussed as a function of various parameters, such as the order of the numerical scheme and the number of grid points per wavelength. A quick review of the up-to-date numerical developments is given on the sheath boundary conditions and on the perfect matching layer in anisotropic media. Possible developments of plasma diagnostics conclude this state-of-the-art of simulations of electromagnetic waves in plasmas.

RÉSUMÉ

Comprendre dans les plasmas les mécanismes régissant la propagation des ondes peut s'avérer complexe, en particulier s' ils sont magnétisés, donc anisotropes et turbulents, donc diffusifs, voire inhomogènes et non stationnaires. La simulation d'un type de plasma avec ses caractéristiques propres passe d'abord par un choix adapté d'équations, suivi par celui d'un schéma numérique accompagné de conditions aux limites spécifiques répondant

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aux contraintes du problème étudié. Nous discuterons l'impact de ces choix sur la qualité des évaluations numériques en fonction de l'ordre du schéma numérique et du nombre de points de grille par longueur d'onde. Une brève revue des sujets d'intérêt portant sur des conditions de bord de type « gaine » et « transparent » en milieu anisotrope est réalisée, et une discussion sur la propagation en plasmas turbulents appliquée, entre autres, aux développements de diagnostics conclut cet instantané sur les travaux actuels.

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1. Introduction

The study of wave propagation in plasmas including experiments covers a lot of domains from astrophysics, space physics, fusion plasmas up to industry using plasmas. Electromagnetic waves are commonly used to determine the plasma characteristics, which allows for a better understanding or control of its behavior. For instance, using waves to deposit energy or momentum at a predefined position requires to know or to rebuild the propagation history of the used waves. The use of electromagnetic waves is obvious when the medium is far away or is too hot. The analysis of the extractable information requires the knowledge of the full history of the wave propagation along its path into the plasma to recover all possible data stored in the received signal, from which the wanted parameters can be extracted using adapted data processing. The prediction of the energy exchange between wave and plasma, which implies to know the wave path and the wave absorption, is of interest to control the plasma or to induce a given perturbation, for example, to stabilize neoclassical tearing modes or to heat a given volume of the ionosphere. To facilitate the interpretations or the predictions of wave propagation behavior in plasmas, simulation is an essential tool if pertinent inputs are used and appropriated model equations are solved using relevant numerical methods with well-posed boundary conditions. However, this requires minimal knowledge about the simulated plasma data. The impact of the approximations made as well as an analysis on the accuracy, including the defaults and limitations of the numerical scheme order and the boundary conditions, should be evaluated and integrated into the interpretation of the results. Once the history of the wave propagation is rebuilt, an additional difficulty has to be overcome, which is the deconvolution of the information accumulated along the wave path. We have also to take into account those introduced by the diagnostic itself. Moreover, simulation permits to study in a synthetic manner different ways to discriminate events relying on the physic effects responsible for each event. Dispersive effects are often used to do that. Interesting solutions found in simulations require significant improvement of the hardware, for example, through the development of a perfectly well-controlled ultra-fast sweeping-frequency reflectometer with a locked phase (which does not exist yet) to measure the wavenumber spectrum of density fluctuations. Although simulation can be used to explore new methods, such an approach should integrate the hardware limitations or should include directly the hardware specifications in order to be relevant for experimental applications.

After these general remarks, we look at the new trends and latest developments achieved in plasma wave simulation. One way to improve the results is to introduce the polarization changes, in particular when the wave goes through an absorption zone [1], a birefringent medium [2], or a turbulent plasma [3]. Simulations of wave propagation can be also used to optimize the parameters needed to compute averages, for instance to provide the turbulence characteristics or macroscopic values and for evaluating the error bars when a restricted number of measurements is processed [4]. Up to now, only few realistic configurations can be fully computed due to the technical limitations of the current computers, to the policy of High Performance Computing (HPC) centers, and to the lack of efficient numerical schemes preserving the physical quantities over long runs [5]. Some limitations are associated with the transparent boundary conditions, which are not able to support several polarizations in inhomogeneous plasmas [6]. No satisfactory solution exists up to now, though effective analytical tools exist to describe wave propagation in plasmas [7], even in highly turbulent plasma cases [8,9]. Experiments in tokamaks [3,4,10] are often beyond the scope of application of these analytical models, and simulation helps us to justify approximate models used for a better interpretation of the measurements. Computation of a transfer function relating the various parameters studied is also a possibility offered by simulation [4]. The emergence of softwares called "Multi-Physics" as COMSOL or of more specialized wave codes such as CST or HFSS makes finite-element simulations more accessible. Although such software may describe non-linear effects [11], however, their applications remain limited. Coupling wave codes with other codes describing more accurately the plasma response encounters an increasing interest, for example, to study absorption and emission mechanisms including kinetic effects [12–16], as well as ponderomotive effects to describe the spread of solitons [17]. As the simulated space size is restricted by the computer potential, a moving mesh following the localized phenomenon can be used. Anyway, mesh optimization should be done using new trends on adaptive methods [18] or an asymptotic preserving scheme [19]. To improve the computational efficiency, the domain decomposition becomes necessary for adapting the changes of numerical parameters scales arising in a simulated system and is still subject to mathematical developments [20]. Questions remain open on how to deal with a resonance and on the relevance of the simulation results: is the addition of an artificial damping factor harmless or does it have a major impact? Recent developments in Mathematics provide an analytical solution for the extraordinary mode in magnetized plasmas [21] that can provide some answers to these questions.