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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

Stéphane Heuraux [a,*], Éric Faudot [a], Filipe da Silva [b], Jonathan Jacquot [c], Laurent Colas [c], Sébastien Hacquin [c], Natalia Teplova [d], Kate Syseova [d], Evgeniy Gusakov [d]

[a] *IJL, UMR 7198 CNRS–Université de Lorraine, BP 70239, 54506 Vandœuvre-lès-Nancy cedex, France*
[b] *Associacao EURATOM/IST, IPFN, Instituto Superior Tecnico, Universidade Tecnica de Lisboa, 1049-001, Lisboa, Portugal*
[c] *CEA IRFM, Cadarache, 13108 Saint-Paul-Lez-Durance, France*
[d] *Ioffé Institute, St Petersburg 194021, Russia*

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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

* Corresponding author.
E-mail addresses: stephane.heuraux@univ-lorraine.fr (S. Heuraux), eric.faudot@univ-lorraine.fr (É. Faudot), tanatos@ipfn.ist.utl.pt (F. da Silva), jonathan.jacquot@cea.fr (J. Jacquot), laurent.colas@cea.fr (L. Colas), sebastien.hacquin@cea.fr (S. Hacquin), n.kosolapova@mail.ioffe.ru (N. Teplova), tinlit@yandex.ru (K. Syseova), evgeniy.gusakov@mail.ioffe.ru (E. Gusakov).

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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.

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.

2. How to choose, for a given wave propagation case, an appropriate model computable as fast as possible?

To answer this question it is better to define a strategy, which is not unique, but may be the following: at first determine what the spatial dimension should be, then consider if the problem is time-dependent or not, after that choose the appropriate spatial domain with the adapted boundary conditions, and if is necessary choose the time domain, and finally implement the necessary diagnostics before choosing the numerical scheme. For the choice of the algorithm, the desired resolution and accuracy have to be chosen in accordance with the described experiment if possible. In fact, other considerations might have to be integrated: necessity for parallel computing or not, possibility of minimizing the numerical operations, optimization of the required memory. All of these choices should include synthetic diagnostic implementation. All these requirements are established assuming that the implemented code is numerically stable, and preserves physical quantities.

2.1. Choice of the spatial dimension

For time computing or memory issues, the studied problem may be reduced to 2 or 1 dimensions, though one has to be aware that some physical effects may be lost, then resulting in misleading interpretations. For example, using a one-dimension simulation of Doppler effects of backscattered waves in a moving plasma induces some limitations, since only the component of the velocity in the studied direction is taken into account in non-relativistic cases, which relies on the fact that only the coupling corresponds to Bragg's rule [22] in one dimension. Let us consider the case of fixed frequency plane waves propagating in a plasma with frozen turbulence moving radially or a radially moving plasma density profile with density fluctuations. In the case of a scattering experiment without reflection at a cut-off layer, these cases are equivalent for the computation, so it can give some freedom to use the fastest simulation. To interpret the simulation results, knowing the numerical model makes it easier to interpret correctly the numerical results, but without this knowledge both computed scattered waves can be also interpreted as time-dependent density fluctuations only. Similar issues exist for 2D simulations of Doppler reflectometry where both the equilibrium plasma and density fluctuations are rotating, therefore the choice of the interpretative model becomes crucial [23]. Some physical effects can only be described using 2D simulation, for example, the probing beam widening induced by the plasma turbulence [24] or the electron cyclotron heating for ITER. 3D-simulations are required to describe electromagnetic wave phenomena in the Earth–ionosphere system in order to account for the highly complex geometry and position-dependent properties of such systems. Similarly it is crucial to take into account multi-reflection and cavity effects in the case of microwave diagnostics used in fusion plasmas such as ITER [25].

2.2. Partial differential equations (PDEs) choice

Once the order of the spatial dimension is defined, the following stage consists in the choice of the model equation set. Most of the situations have been considered in [24]. In order to introduce up-to-date considerations on the PDE set describing wave propagation in plasmas, the Maxwell equations coupled with a plasma response expressed in terms of currents and charge separation induced by the wave are recalled. Depending on the plasma modeling the wave dynamics includes or not kinetic effects or non-linear contributions. The choice of plasma modeling determines the physical mechanisms taken into account during wave propagation. The set of PDEs describing wave propagation can be written formally independently of the plasma model used as follows:

$$\begin{cases} \nabla \cdot \vec{\mathbf{E}} = \dfrac{\rho}{\epsilon_0} \quad \text{Poisson's law} \\ \nabla \cdot \vec{\mathbf{B}} = 0 \quad \text{magnetic flux conservation law} \\ \nabla \times \vec{\mathbf{E}} = -\dfrac{\partial \vec{\mathbf{B}}}{\partial t} \quad \text{Faraday's law} \\ \nabla \times \vec{\mathbf{B}} = \mu_0 \vec{\mathbf{J}} + \dfrac{1}{c^2}\dfrac{\partial \vec{\mathbf{E}}}{\partial t} \quad \text{Ampère's law} \end{cases} \tag{1}$$

+ PDEs describing the density current $\vec{\mathbf{J}}$ and ρ as functions of $(\vec{\mathbf{E}}, \vec{\mathbf{B}})$, where ρ is the charge density, ϵ_0 is the dielectric constant of vacuum, μ_0 is the permeability of vacuum, and c is the speed of light in vacuum. The most general description uses Vlasov's equation with the associated definition of $\vec{\mathbf{J}}$ and ρ [24], in which resonant wave–particle interactions as the thermal effects are included.

Neglecting ion responses through a cold plasma approximation with density n_e and magnetic field $\vec{\mathbf{B}}_0(r)$, the propagation of an electromagnetic wave at high frequency is described by the following coupled partial differential equations (PDEs):

$$\begin{cases} \nabla \times \nabla \times \vec{\mathbf{E}}(\mathbf{r}, t) = e\mu_0 n_e \dfrac{\partial \vec{\mathbf{v}}}{\partial t} + e\mu_0 \dfrac{\partial n_e}{\partial t}\vec{\mathbf{v}} - \dfrac{1}{c^2}\dfrac{\partial^2 \vec{\mathbf{E}}(\mathbf{r}, t)}{\partial t^2} \\ m\dfrac{\mathrm{d}\vec{\mathbf{v}}}{\mathrm{d}t} = q\vec{\mathbf{E}}(\mathbf{r}, t) + q\vec{\mathbf{v}} \times \vec{\mathbf{B}}_0(r) \end{cases} \tag{2}$$

where the density n_e includes equilibrium density and density fluctuations profiles, and the magnetic field $\vec{\mathbf{B}}_0(r)$ depends slowly on time and space. However, this set of PDEs does not have up to now any stable numerical discretization in highly fluctuating plasmas. New algorithms are under development to find a precise time-conservative and stable one. Another way consists in using the potential vector $\vec{\mathbf{A}}$ and the scalar potential ϕ. This modeling has to be considered due to the fact that the PDEs associated with wave propagation are simply written as follows:

$$\begin{cases} \Delta\phi - \dfrac{1}{c^2}\dfrac{\partial^2\phi}{\partial t^2} = -\dfrac{\rho}{\epsilon_0} \\ \Delta\vec{\mathbf{A}} - \dfrac{1}{c^2}\dfrac{\partial^2\vec{\mathbf{A}}}{\partial t^2} = -\mu_0\vec{\mathbf{J}} \end{cases} \tag{3}$$

where $\vec{\mathbf{A}}$ and ϕ are coupled through the Lorentz gauge $\frac{\partial\phi}{\partial t} + c^2\nabla\cdot\vec{\mathbf{A}} = 0$, where c^2 is the speed of light. However, we have to be careful about the definition of ρ and $\vec{\mathbf{J}}$ as it is done in Jackson's book [26], where c^2 is defined as the phase velocity. To go back to the electric and magnetic fields, we need to compute both, knowing that $\vec{\mathbf{E}} = -\nabla\phi - \frac{\partial\vec{\mathbf{A}}}{\partial t}$ and $\vec{\mathbf{B}} = \nabla\times\vec{\mathbf{A}}$, and then to solve the equations of the motion or Vlasov's equation, or use a J-solver to deduce the source terms ρ and $\vec{\mathbf{J}}$. Although the numerical complexity of the potential description is on the same order of magnitude as that of Eq. (2), it requires additional operations. In fact, the Maxwell equation solver coupled with the J-solver is the most used and developed approach, but some problems (stability, energy conservation) arise for the large number of iterations required for ITER [27] or in the case of "high"-frequency waves in the ionosphere [28]. These PDE sets permit in principle to treat the time-dependent wave propagation cases. However, the time evolution of plasma parameters should have slow time scale to avoid unphysical effects as the cut-off layer motion moves faster than the wave motion, which is theoretically possible but unrealistic in practice. Even if unrealistic cases can be computed setting bad inputs, the PDE set can describe all the possible mechanisms of plasma–wave interaction such as wave-trapping, multi-scattering, diffraction, etc., if the mesh and the input parameters used are relevant to compute it. Consequently, an interplay between the physical requirements and the computation constraints has to be traded off for computing-time optimization.

The PDE sets written so far consider only a linear response to the studied wave solicitation. Going towards non-linear description requires to couple a wave equation or a Maxwell equation code to a code assessing the non-linear plasma responses for the current density and charge separation, including non-linear effects [29]. The full non-linear response can be provided by a particle-in-cell code [12] or using a kinetic equation [30]. Taking into account the ponderomotive effects, solitons or solitary waves can be studied. There are different ways to approximate these non-linear responses. The most common approach relies on a Boltzmann equilibrium for the electrons with a scalar ponderomotive potential, which includes partially the polarization of the launched wave, but is unable to describe correctly the non-linear magnetic field generation. Despite these limitations, this approximation allows us to study the effects of a slowdown of the soliton-induced turbulence, as it will be shown later. This kind of description assumes also that the non-linear plasma response is instantaneous. For the Zahkarov equations used in simulations of artificial wave heating of the ionosphere [31], the non-linear response can propagate, and yields to different kinds of solitary waves, depending on the plasma response velocity [32].

Other kinds of non-linear effects associated with polarization changes exist, as mode conversion [33,34], cross-polarization induced by turbulence [3] or by non-linear current density excitation [35]. A wave going through a plasma with a relativistic motion can also introduce polarization variations due its intrinsic birefringent feature [36]. Most of these phenomena could be used to develop new kinds of plasma diagnostics. The PDE sets describing the last samples are rather complicated to solve as they consist in two wave equations coupled via non-linear terms plus differential equations giving the plasma responses. A good choice for the numerical scheme is essential to solve numerically such coupled PDE set. Then significant developments are still required, and the main rules to follow will be presented in the following paragraph.

2.3. On the choice of algorithm, boundary conditions, and implementation

The first approach to solve a problem with simulation is usually performed using existing codes or tools available in the surrounding environment. These tools may be adapted to the numerical resolution of the phenomenon to be simulated if the choice of the numerical scheme or the method used is relevant. As the computation capabilities increase, it is quite natural to take into account more sophistications, but on the other hand more complexity is introduced in the simulated systems. In particular, commercial softwares are now optimized using highly evaluated mesh refinement algorithms, and other sophisticated tools. Own-developed adapted algorithms are often necessary to avoid unphysical results, as illustrated in Fig. 1, where an expected behavior is found for the potential and an unrealistic one for the current density.

For these reasons, it is useful to recall some major issues involved in the discretization of a model equation. The most appropriate methods are implicit ones due to their stability. They are generally associated with a sparse matrix inversion for which significant improvements have been done. The finite-element method is also more adapted to complex geometries than the finite-difference methods. However, when the simulated environments become strongly anisotropic, finite elements may be ineffective and may exhibit a high level of numerical noise. This kind of problem can be solved by using an asymptotic preserving scheme [19], which is suitable to support high levels of anisotropy. Current progresses on this issue are important and are often quickly integrated into commercial softwares. The finite differences explicit schemes can be useful to simulate very big mesh size over long computing times, but their stability becomes an issue [5] and an

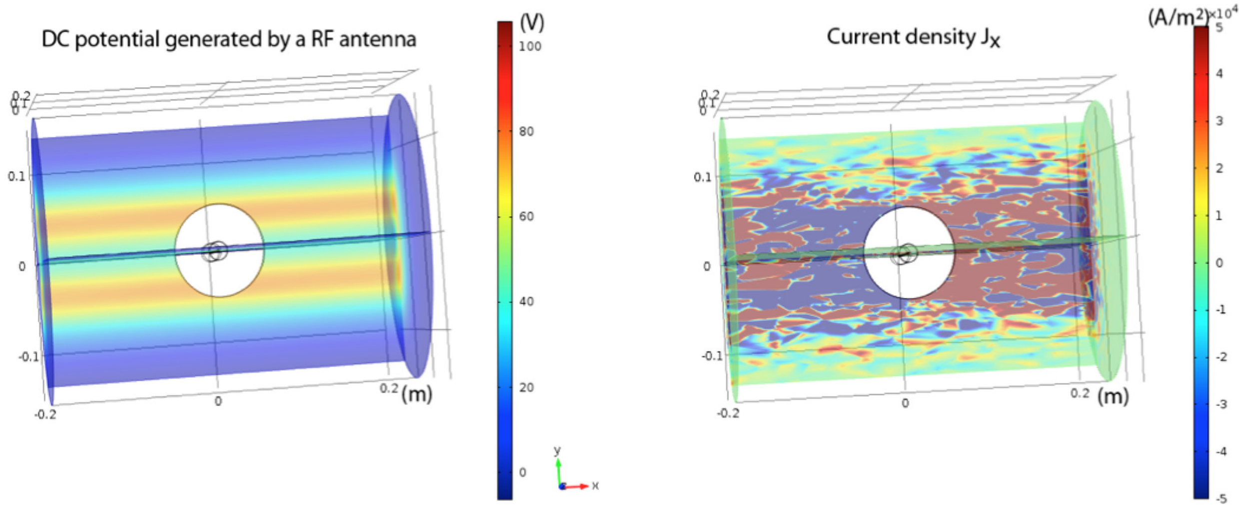

Fig. 1. (Color online.) Computed DC potential (left) and x-component of current density, which appears unphysical, (right) induced by an RF antenna (white circle), including boundary sheath conditions with very high anisotropy of the conductivity $\sigma_{\parallel}/\sigma_{\perp} = 10^5$, $n_e = 10^{18}$ m^{-3}, $B_0 = 1$ T.

adapted geometry has to be used. A semi-implicit scheme (explicit in time) can also be a solution to solve this stability problem under standard stability conditions, especially if specific boundary conditions are used [37,38]. The solutions found are not always satisfactory due to the lack of numerical accuracy or intrinsic numerical dispersion. To overcome this kind of numerical problems, if possible, one can upgrade the numerical scheme by changing the order of the scheme. Generally more computational resources in terms of memory, and longer computation time for one time step are needed. However, the accuracy improvement can permit to compensate this slowing down by reducing the number of points per wavelength. Consequently, a higher-order numerical scheme should permit to improve code performance and to reduce numerical dispersion. But as the scheme order increases, the stability conditions are more and more restrictive [39]. So, an optimal order and compact scheme are to be found to optimize the resolution and the necessary amount of memory [40]. In practice, the 4th order is the most widely used. To finish on algorithm considerations, the best thing to do to avoid the pitfalls of numerical dissipation is to use conservative schemes, which can be dispersive, but marginally stable. This is a real challenge for the description of an X mode [5] or of a 3D multi-mode code [41].

For these numerical schemes, the issue of boundary conditions has to be addressed, and the result is generally reliable as long as these conditions are regular (slowly varying). As soon as the frames of the spatial variations in the computational domain boundaries are in the order of magnitude of the wavelength or smaller, existing boundary conditions no longer correspond to the simulated phenomena. For example, sheath boundary conditions have to be treated carefully to avoid unphysical results [6]. Not all the cases are describable numerically, such as a hybrid resonance cone crossing the edge of the computational domain. This case presents a wide variation in spatial scale and a strong anisotropy in which domain decomposition is ineffective to adjust the resolution and mesh. The same is true for the coupled system of equations describing the conversion of modes involved in the heating process [32–34]. Given the volume of objects to be simulated, such as ITER or ionospheric surveyed areas, and the frequencies in use, these aspects become essential to have relevant simulation results. To assess the plasma responses to electromagnetic loads, including nonlinear relativistic effects, one must couple Maxwell's equations with a particle code, which has been done for laser–plasma interaction [13], heating ion cyclotron [12], operation of a gyrotron [16] or interaction of an aircraft with a plasma [42]. These simulations require access to the most powerful computers and thus are submitted to the policy of computer centers.

3. On the possible ways to develop diagnostics using electromagnetic waves

Simulation is an interesting tool to develop and to improve diagnostics using electromagnetic waves, since it permits to have a deeper understanding of the basic physics connected to the studied diagnostic. In addition, it provides guidelines to establish new theoretical models, to test and to validate new concepts or data processing, and to compute transfer functions able to improve the interpretative model. Just to illustrate the possibilities of simulations to improve the understanding of the physics of diagnostics, Fig. 2 shows the role of the wave number spectrum on the behavior of the scattered wave. The first case (see Fig. 2, left) contains wave numbers able to induce only forward scattering, and effectively the scattered field is in the same direction as the probing wave. In this case, there is no Bragg backscattering. The second one (see Fig. 2, right) corresponds to a wider wavenumber spectrum including values fulfilling the Bragg rule and gives completely a different result where the localized turbulence zone seems to be an isotropic source of the incoherent scattered wave. These pictures represent the difference between the total field squared with and without turbulence, and have been obtained using an averaging over 200 independent samples. Here the role of the averaging is clearly noticeable. The transition zone between

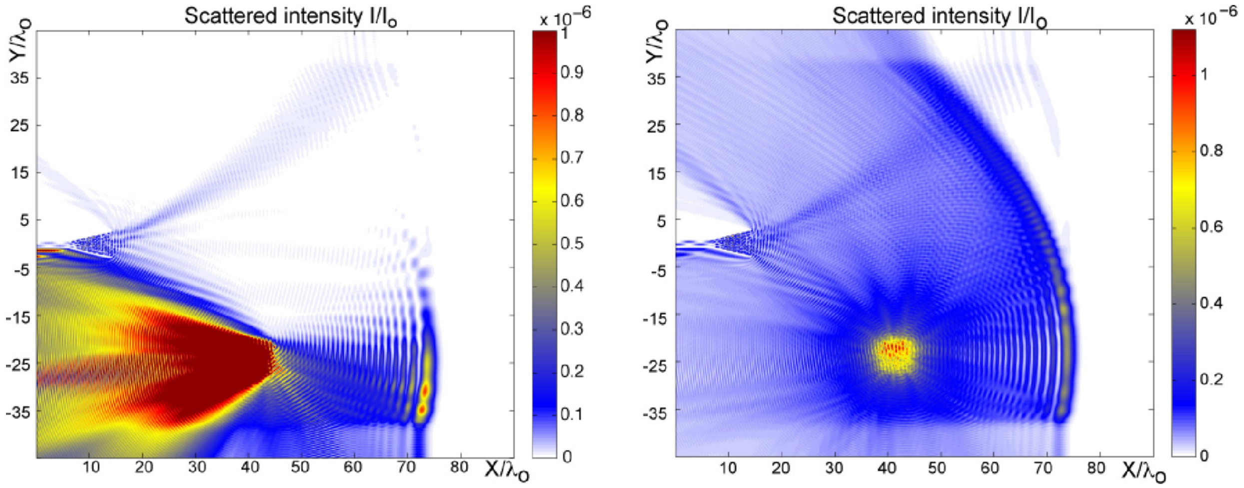

Fig. 2. (Color online.) Role of the wavenumber spectrum on the scattered intensity E_s^2 averaged over 200 samples of turbulent matrices in the case of linear density profile and localized density fluctuations (square shape of $7.5\lambda_0$, length side centered at $(-25, 41.25)$) in two cases (left) when forward scattering dominates and (right) with dominating Bragg scattering (probing frequency $\nu = 40$ GHz, $\delta n = 0.001 n_c$, wave injection with a horn at $Y = 0$).

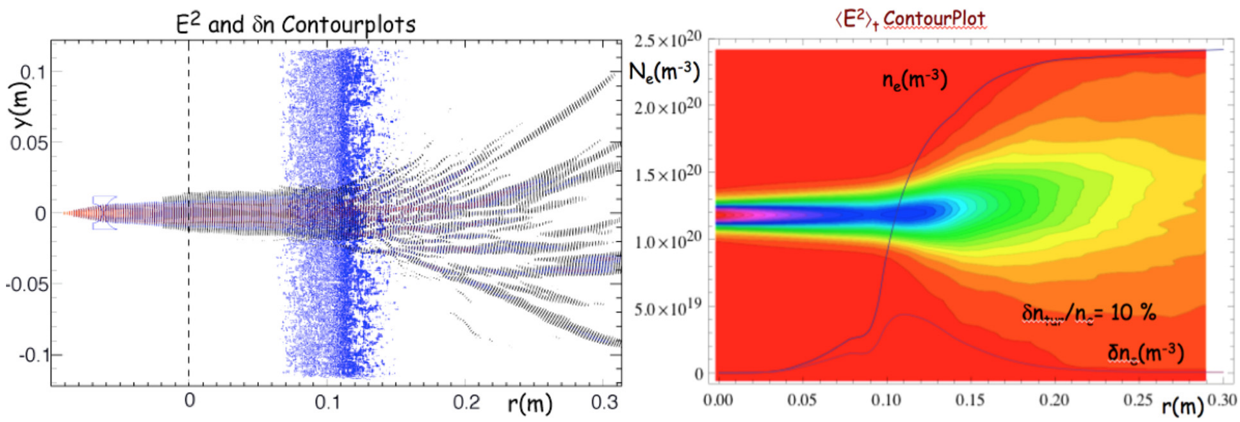

Fig. 3. (Color online.) Contour plots of the wave intensity (left) and after time averaging (right) on which are superimposed the density profile and the density fluctuation profiles.

the central zone and the boundary conditions can be also easily highlighted. The results suggest the possibility to build a simplified model to describe the scattering processes over the entire probing zone, assuming the existence of an intensity source point. The beam widening induced by forward scattering at the plasma edge is shown in Fig. 3, on the left, the intensity for one run (no averaging) is shown and exhibits a multi-sub-beam structure generated after the propagation of a Gaussian beam through a turbulent zone. Beam spreading is evident looking at the vacuum-plasma interface, but only after averaging, it appears that the spread beam recovers its Gaussian shape. These illustrations are just an application of the recent works showing that the average over a large number of samples enables to extract turbulence properties or determine the influence of density fluctuations on the diagnostic measurements. The first work concerning the extraction via an averaging technique of the radial wavenumber spectrum from fast sweep frequency reflectometry data was published ten years ago [43] and was improved later by using transfer function computation [4]. More recently, it has been found that in the 1D case, even if we are above the Born approximation [22], in average, the intensity of the probing wave follows the Born approximation results unless the Bragg backscattering dominates [9]. So, the use of statistical properties of a large set of signals can open new ways to obtain more information about the probed fluctuating medium, especially when the Born approximation is not valid. Since the information about the turbulence is directly linked to the scattered wave whose level is proportional to the local intensity of the probing wave and the refractive index fluctuations, the knowledge of the probing intensity is essential. The role of the simulation is crucial to give access to the local intensity of the probing wave beyond the Born approximation as shown here. All future improvements and new concepts of diagnostics should integrate that averages give access to turbulence properties. When the instantaneous wave probing intensity is inaccessible but can be approximated using averaging, a possible interpretative model can be developed. Based on this idea, we analyze now different configurations in which the probing electric field has to be evaluated everywhere by full-wave simulations

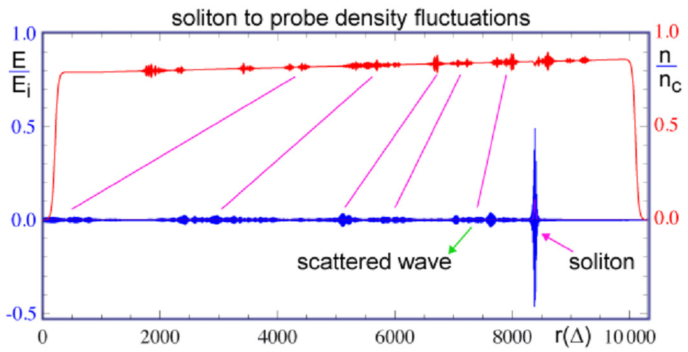

Fig. 4. (Color online.) Soliton interacting with bursty density fluctuations, showing a good localization of the scattered wave.

during the measurement. In fact, we also need to identify the main coupling term between the probing wave and plasma fluctuations, or between the probing wave polarization and the polarization changes induced by the plasma.

In the first example, we assume that there is no polarization variation and the Bragg backscattering is the main mechanism generating the scattered wave. If the spectrum of the density fluctuations is wide enough, the scattered signal can come from everywhere along the path of the probing wave in the probed medium, except if the probing field is a pulse or a soliton, which are spatially localized. For a known shape of the probing electric field at a given position in the plasma, it is possible to determine which wavenumber range contributes to the Bragg backscattering. To evaluate now the position of this scattering zone, measurements of time of flight are required. But to ensure a good spatial resolution, the envelop of the probing wave should be as narrow as possible. That is to say that a very short pulse should be used, but due to strong dispersive effects, the pulse becomes wider and wider during its propagation in the plasma. So quickly, we lose the spatial resolution when the pulse propagates into the plasma. An optimal value for the pulse width can be determined [44]. Whatever the pulse width needed to minimize the dispersive widening, it gives a poor spatial resolution. One possibility to have narrow pulses without dispersion in collisionless plasmas is given by solitons [32], for which non-linear effects compensate dispersion. However, the knowledge of the plasma temperature is required to compute the amplitude and soliton velocity, which is no longer linked to the group velocity due to non-linear effects. Thus we have increased the spatial resolution and provided a localized image of the perturbation (see Fig. 4). However, the localization becomes more difficult to obtain as the soliton velocity has to be known until the interaction zone is reached and the group velocity of the scattered wave has to be determined. This supposes that the position of the density perturbation is inferred from the time of flight, which is not easily determined, especially if the plasma temperature changes significantly. When the temperature decreases, the non-linear effects induces an increase of the soliton's amplitude, and thus an acceleration of the soliton. So, in fact both the amplitude of the scattered field and the effective wavenumber spectrum range probed by the soliton are changed. Here, to interpret correctly the measurements based on soliton, probing simulation is required to have access to the absolute value of the density perturbations, which is deduced from the local value of the probing wave amplitude and its localization by computing the needed velocities. However, this diagnostic gives a direct access to the spatial distribution of the density fluctuations only if the wavenumber spectrum of the soliton covers all the spatial scales of the turbulence in the probed zone.

Other new developments of diagnostics deal with polarization changes in anisotropic plasmas. The rare developments of diagnostics using polarization changes are probably a consequence of the 3D-nature of the problem, which induces difficulties linked to inhomogeneity and anisotropy. To identify the difficulties, let consider a plane wave with a given polarization propagating obliquely up to a shear magnetic field layer within an inhomogeneous moving plasma, and try to answer the following question: what should the wavefront evolution of this plane wave during its propagation be? To answer this question, a possible solution, at this moment, can only come from a 3D Maxwell equations solver coupled to a J-solver including all the electric components. In such simulations, the wave absorption has also to be taken in account to integrate most of the mechanisms inducing polarization changes, but in these cases the stability of the numerical scheme is limited. In spite of these difficulties, the use of different polarizations to probe a plasma has been applied in different cases, the results cross-checked, and cross-correlated in [45]. As mentioned before, cross-polarization scattering has been used to determine the magnetic field fluctuations [3,46]. Works on wave polarization changes in turbulent atmosphere have been published [47]. Polarization changes can also be associated with mode conversion and applied to new heating scenarios in fusion devices [33] or connected to the propagation through anisotropic media in the presence of relativistic effects [36] or of an inhomogeneous magnetic field [48]. In plasmas, the polarization changes have not been really considered as a tool to characterize density fluctuations. However, the role of density fluctuations has been investigated to explain polarization variations of electromagnetic solar emission [49]. To go further in the development of diagnostics using polarization changes, the main difficulty is to solve a coupled PDE set in which the coupling terms depend on the fluctuating plasma parameters. The computation of the electric field for each polarization is required to interpret the measurements. This kind of diagnostics is able to provide complementary results, and gives access to turbulence parameters not available with other diagnostics; for example, magnetic field fluctuations are only accessible via cross-polarization scattering [3].

4. Discussion and conclusions

The state of the art in the simulation of wave propagation in plasmas can be summed up like this: 3D full-wave codes will be soon operational to provide realistic results that could be compared to experiments, provided the mesh size stays small enough [41]. The use of commercial softwares is essentially limited to the frequency domain and are still marginally used due to the fact that they suffer from the lack of relevant boundary conditions, such as sheath boundary conditions or multi-mode Perfect Matching Layer, which is still under development. They are also restricted to low anisotropy levels. However, an improvement can be done using asymptotic preserving schemes. Generally speaking, the most efficient codes remain the "home-made" ones. Their maturity comes from specific numerical schemes, which are stable for any computation time and conservative (no numerical dissipation). Even if High Performance Computing offers large capabilities, a long gap has still to be filled before running relevant ITER cases in reflectometry or other experiments requiring more than 100 wavelengths in each direction. In lower dimensions, nonlinear plasma responses (wave–particle interactions, thermal effects, relativistic corrections...) can be taken into account. As simulation of wave propagation in magnetized plasmas becomes more and more reliable, it will become a necessary tool to interpret experimental data especially well adapted to the computation of transfer functions based on statistical averaging. In this paper, the utility of averaging over probing wave intensity has been demonstrated, showing that the Gaussian shape of a probing beam is conserved during propagation through a turbulent plasma, even if the beam is spread. The averaging method also allows us to evaluate the probing wave intensity appearing in the expression of the scattered field and then to build a transfer function that can be valid even beyond the Born approximation. Thus the interest of simulation tools becomes obvious for the interpretation of measurements and for the development of new diagnostic concepts. That permits to identify the basic mechanisms, the main dependencies, and to give new methods allowing to determine the wanted parameters. For the characterization of the plasma turbulence, the knowledge of the probing wave intensity is the key point. To illustrate soliton probing, the presented simulation shows that it is possible to have an image of the density fluctuations using narrow solitons. Though there is a price to pay: the soliton velocity has to be known at any time, which is not trivial due to the fact the soliton speed is a function of its intensity. Knowing also that the soliton width is linked to its intensity and that part of the soliton energy is lost during its interaction with density fluctuations, this restricts the spatial resolution of this method of turbulence characterization. The advantage to use soliton probing is to avoid dispersive effects that affect the propagation of pulses. The dispersion effects can be reduced using wide pulses, but then the spatial resolution is lost as it is at fixed frequency. It is possible to recover partially the spatial resolution by sweeping the probing frequency and to benefit from the localization of the Bragg backscattering. Two other parameters have to be included in the design of a new diagnostic: the damping of the probing wave and the local variations of the refractive index. All these last remarks give a guideline for designing new promising diagnostics based on the polarization changes, which should enable one to assess more precisely the wanted quantities or to give access to unexplored ones.

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