

Propagation of radio frequency waves through turbulent plasmas

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The practical and economic viability of tokamak fusion reactors depends, in a significant way, on the efficiency of radio frequency (RF) waves to deliver energy and momentum to the plasma in the core of the reactor. The RF electromagnetic waves, excited by antenna structures placed near the wall of a tokamak, have to propagate through the turbulent edge plasma along their path to the core of the fusion device. In present day experiments, the radial width of the edge region and scrape-off layer is of the order of a few centimeters. In ITER, and in future fusion reactors, this width will be of the order of tens of centimeters. Any modifications to the properties of RF waves in the edge region can have deleterious effects on the efficiency and spatial distribution of power coupled to the plasma. This could affect, for example, the stabilization of the neoclassical tearing mode in ITER by electron cyclotron RF waves. Thus, it is imperative to properly understand the propagation of RF waves through plasma turbulence. This paper is on a multi-pronged, theoretical and computational, approach that is being pursued to quantify the effect of edge plasma turbulence on the propagation of RF waves. The theoretical and analytical models are based on solutions of the Faraday-Ampere equation in a magnetized plasma (1-3) and on the Kirchhoff tangent plane approximation (4). An effective medium approach has been developed so as to approximate the permittivity of a turbulent plasma by analytical expressions (5). The computations are being carried out with a newly developed code ScaRF that solves Maxwell's equations in three-dimensions for an arbitrarily assigned plasma permittivity (6).

THEORETICAL MODELING OF SCATTERING OF RF WAVES

A full-wave theoretical model, using Maxwell's equations, has been developed for scattering of RF plane waves by blobs and filaments embedded in a magnetized plasma (1-3). The spatial structure of the electric and magnetic fields is given by the Faraday-Ampere equation, and mathematical techniques developed for Mie scattering are used to solve the wave equations for a cold plasma permittivity. We have formulated a complimentary analytical model based on the Kirchhoff's tangent plane approximation [4]. The Kirchhoff method has commonly been used for studying scattering of electromagnetic waves from rough surfaces. The basis of the Kirchhoff approximation is built upon the theory of physical optics. In this approximation, the scattered field due to planar turbulence is determined by the wave fields on the surface of the turbulence separating two different plasma densities. Each point on this surface is assumed to be part of an infinitely extended plane that is along the local tangent at that point. Consequently, the Kirchhoff approximation, along with physical optics, leads to the study of reflection, refraction, and side-scattering of RF waves. This not only simplifies the modeling of RF scattering but, more importantly, gives physical insight into several, experimentally significant, aspects of scattering. We find that the spectrum of the RF fields is modified along, and across, the direction of the magnetic field. We have derived analytical expressions for the changes in the wave spectrum based on the spatial variation of the density fluctuations. The theory also predicts linear coupling of RF waves due to turbulence. For example, in the electron cyclotron range of frequencies, an incident ordinary wave can couple some of its power to the extraordinary wave in the presence of fluctuations. The theoretical results are being validated by full-wave simulations of RF scattering by different forms of plasma turbulence.

COMPUTATIONAL STUDIES ON SCATTERING OF RF WAVES

A full-wave electromagnetic computational code ScaRF, based on the finite difference frequency domain (FDFD) method, has been developed to study the effects of density turbulence on the propagation of RF waves (6). The anisotropic plasma permittivity used in the code is that for a magnetized, cold plasma. The code was initially used to study the propagation of an RF plane wave through a spatially modulated, periodic, density interface. Such an interface arises in the edge region due to magnetohydrodynamic instability and/or drift waves. Figure 1 shows the effect of a sinusoidal density perturbation on the propagation of a plane wave (incident from the top of the figure). Besides the transmitted wave through the density perturbation, there is a reflected wave as well. The Fourier spectrum of the transmitted RF electric field, Fig. 2, shows a broadening of the spectrum as the wave propagates away from the density fluctuation. The results from ScaRF are being used to validate the analytical results obtained from our theoretical models and for determining the limitations of the Kirchhoff approximation. While ScaRF has been used to study a periodic density fluctuation, the code is general enough to include different varieties of density fluctuations in the edge region - such as blobs and filaments, and spatially random fluctuations.

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MODELING THE PERMITTIVITY OF PLASMAS IN THE SCRAPE-OFF LAYER

The theoretical and computational studies on scattering, using either the full-wave approach or the physical optics model, require a proper description of the plasma permittivity in the turbulent edge region. The tenuous plasma in this region is a mix of fluctuations with a broad range of spatial correlations. Electromagnetic homogenization, or “effective medium approximation”, is the process of estimating the effective electromagnetic properties of composite materials. We have generalized this approximation, following the Maxwell-Garnett approach to describe the plasma permittivity in the scrape-off layer (5). Our formulation is suitably adapted for magnetized plasmas and for RF waves that are commonly used for heating and current drive. The advantage of this approach is that we can describe the turbulent plasma as an effective homogeneous medium for which the permittivity is suitably approximated. This eliminates the need to have a detailed description of the edge plasma - an experimentally formidable task. The effective permittivity is being implemented in a computational code and will be validated against specific models of the plasma permittivity.

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