Fast Wave Evanescence in Intermittent Edge Plasmas

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LODESTAR RESEARCH CORPORATION
2400 Central Avenue
Boulder, Colorado 80301

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Lodestar Research Corporation, Boulder, CO 80301, USA

Abstract. Radio frequency waves used for heating and current drive in magnetic confinement experiments must traverse the strongly turbulent and intermittent scrape-off-layer (SOL) and edge plasma before reaching the core. In particular, ion cyclotron range of frequencies (ICRF) waves interact with turbulence-generated blob-filaments in the SOL. Here, we calculate the effective scale length for evanescence of an incident fast wave (FW) when there is a significant disparity between the average density, the density between blobs, and the peak blob density. This is the case of strong edge intermittency, which is typical in tokamak experiments. Several models are explored. It is found that although the FW wavelength is long compared with the cross-field dimensions of the turbulence, the FW does not simply average over the turbulent density, rather the evanescence is essentially controlled by the density between blobs. This effect, which can decrease antenna coupling to the core plasma relative to mean-field estimates, is significant when the distance between the antenna and the nominal FW cutoff (where propagation begins) is long.

Keywords: ICRF, blobs, fast wave, evanescence, coupling
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INTRODUCTION

Waves in the ion cyclotron range of frequencies (ICRF), routinely used for heating and current drive in fusion experiments, must traverse the scrape-off layer (SOL) and edge plasma before reaching the core. Both the SOL and edge plasmas (the regions outside and just inside the separatrix) are strongly turbulent. It is by now well understood that this turbulence takes the form of intermittent blob-filaments[1,2] which are formed in the edge and propagate across the SOL. These blob-filaments or "blobs" are B-field aligned structures that have long parallel scale lengths (many meters) and short perpendicular scale lengths, on the order of a few cm's. On time scales of interest for ICRF, the blobs are essentially frozen in time. Thus an rf wave sees a spatially intermittent plasma, i.e. a low density background plasma on which is superimposed a number of higher density blobs.

In previous work,[3] we studied the scattering of propagating fast waves (FWs) and slow waves from these filamentary structures. Concepts such as the scattered power fraction, scattering-induced mode conversion, and the effective blob scattering cross-section were addressed. Here, we consider a related question. How does spatial intermittency affect the FW when it is evanescent? For densities below the FW cutoff,[4] evanescence limits the coupling of the wave fields at the antenna to the core plasma. Because evanescence is sensitive to density, it is of interest to address the effect of sparse, but high density, blobs on the evanescence rate. Of interest will be the blob radius δ in the perpendicular plane, the packing fraction f_p (fraction in the perpendicular plane of the blob-covered area relative to total area), the peak blob density n_b and the background density $n_0 << n_b$. We will consider the limit $k_{\perp fw}\delta <<$ 1 (easily satisfied in practice), and the sublimit $f_p << 1$ (well satisfied in the far SOL). Thus typically evanescence inside a blob is negligible, but evanescence occurs between blobs when n_0 is below the cutoff density.

1D MODELS

Two simple 1D models, the isolated blob and a periodic blob "lattice," serve to introduce the basic concepts and dependencies. The geometry is shown in Fig. 1.

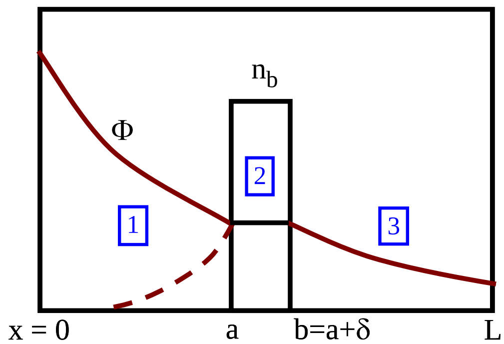

FIGURE 1. Geometry for 1D rf-blob interactions. The evanescent wave-field Φ is launched from the left into a low density plasma region (1). It interacts with a blob of width δ and density n_b in region (2). Part of the wave is back-scattered (dashed), and the rest propagates through the blob and on into region (3).

The scalar wave equation

$$\frac{\partial^2 \Phi}{\partial x^2} + k^2 \Phi = 0 \tag{1}$$

is solved in the various regions and matched, taking $k = 0$ inside the blob, and $k = i\kappa$ outside the blob. We define the evanescent decay factor F, and the effective evanescence rate in the presence of blobs q by

$$e^{-qL} \equiv F = \frac{\Phi(L)}{\Phi(0)} \tag{2}$$

For an isolated blob the general result depends on κ, δ and L through the packing fraction $f_p = \delta/(L-\delta) \approx \delta/L$ and κL and takes the form

$$\frac{q}{\kappa} = \frac{1}{\kappa L} \ln\left(\frac{1 + Re^{-\kappa a}}{Be^{-\kappa(L-b)}}\right), \quad R = \frac{\kappa\delta e^{-\kappa a}}{2 + \kappa\delta}, \quad B = \frac{2e^{-\kappa a}}{2 + \kappa\delta} \tag{3}$$

For $f_p << 1$ we find

$$\frac{q}{\kappa} = 1 - \frac{1}{2} f_p \left(1 - e^{-\kappa L}\right) - \frac{1}{8} f_p^2 \kappa L \left(1 - e^{-\kappa L}\right)^2 + \ldots \qquad (4)$$

consequently, the deviation of q from κ is of order f_p if $\kappa L \sim 1$. For $\kappa L >> 1$, but f_p arbitrary, we find

$$\frac{q}{\kappa} = 1 - f_p + \frac{\ln(1 + f_p \kappa L / 2)}{\kappa L} + \ldots \qquad (5)$$

For a blob-lattice model (i.e. an infinite train of blobs) backscattered waves are additionally retained in region (3) and a new boundary condition is added, the matching of d(lnΦ)/dx at x = 0 to its value at x = L. In this case the $f_p << 1$ result is

$$\frac{q}{\kappa} = 1 - \frac{1}{2} f_p - \frac{1}{8} f_p^2 \frac{\kappa L}{\tanh(\kappa L)} \qquad (6)$$

while for $\kappa L >> 1$ and f_p arbitrary neighboring blobs in the lattice do not interact, so the leading asymptotic result is the same as in the isolated blob limit.

In both the isolated and blob-lattice cases, the waves evanesce more slowly than they would in the absence of blobs, with the deviation of q from κ being of order f_p. Note that the mean density (averaging over the turbulent structures) does not enter the calculation. Numerical plots of the general results are shown in Fig. 2. The analytical expansions cover a wide variety of cases.

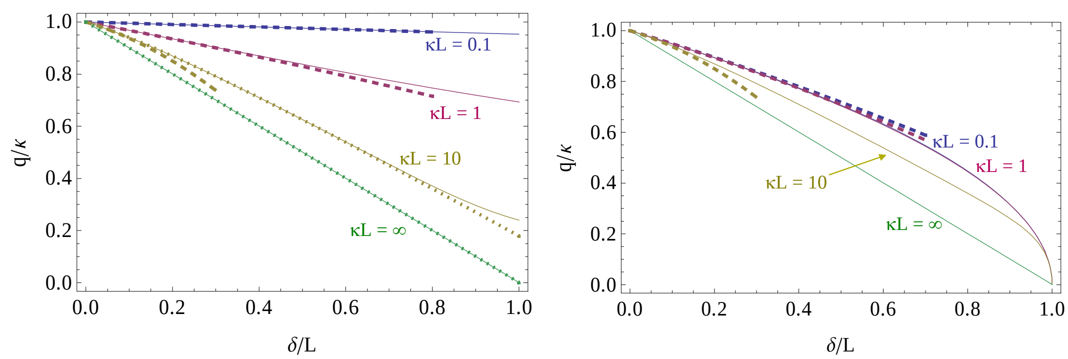

FIGURE 2. Normalized evanescence length for various values of κL in the single-blob (left) and blob-lattice (right) models. Solid curves are numerical, dashed curves are the $f_p << 1$ expansions, and dotted curves (left) are the $\kappa L >> 1$ expansions.

2D MODEL

The rf blob-scattering formalism developed earlier[3] can also be modified to apply to the case of evanescent wave fields, of interest here. In place of Eq. (1) the full vector wave equation for FW fields is employed, and electromagnetic matching conditions are applied at the blob interface. For evanescent waves, Bessel functions in Ref. 3 are continued into the complex plane. Results are summarized in this section, and will be published in detail elsewhere.

In the presence of many randomly spaced blobs in the 2D perpendicular plane, the wave interacts with the blobs as if they were isolated when the inter-blob spacing is large compared with $1/\kappa$, i.e. $\kappa L_x >> 1$. We invoke the $\kappa\delta << 1$ and $k_b\delta \rightarrow 0$ limits for the scattering coefficients. The evanescence factor in the 2D case is defined as the ratio at $x = L_x$ over $x = 0$ of the rms average of the E_y field of the FW (where x is the direction of evanescence) and the 2D blob packing fraction is given by $f_p = \pi\delta^2/(L_x L_y)$. After detailed calculations in the asymptotic limit $\delta << \kappa^{-1} << L_x$ we find

$$\frac{q}{\kappa} = 1 - f_p g(\zeta) \tag{7}$$

where $\zeta = \kappa L_x/2$ and $g(\zeta \rightarrow \infty) = 1$. When expressed in terms of the packing fraction, this result is the same as the 1D result in the large κL limit. The 2D field patterns show that the blob reduces the evanescence in its vicinity, on the scale $1/\kappa$.

DISCUSSION AND CONCLUSIONS

Although the FW wavelength is long compared with the dimensions of the turbulence (i.e. the blob scale δ), the FW does not simply average over the turbulent density. Rather, the evanescence is controlled by the density between blobs and the blob packing fraction f_p. Within factor-of-two accuracy for the coefficient of f_p, we find that

$$q \approx \kappa(1 - f_p) \tag{8}$$

where q is the net evanescence rate and κ is the rate between blobs. For rough estimates, the relevant definition of packing fraction is the fractional area covered by blobs that have density greater than the FW cutoff, or much greater than background.

Intermittency decreases antenna coupling to the core plasma relative to estimates based on the mean density profile. The effect is significant when the distance between the antenna and the nominal mean FW cutoff (where propagation begins) is long. This result provides additional motivation for both predicting and controlling the SOL density in ITER since antenna loading[5] is sensitive to the degree of evanescence.

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