Slow Wave Propagation and Sheath Interaction for ICRF Waves in the Tokamak SOL

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Abstract. In previous work we studied the propagation of slow-wave resonance cones launched parasitically by a fast-wave antenna into a tenuous magnetized plasma. Here we extend the previous calculation to "dense" scrape-off-layer (SOL) plasmas where the usual slow wave is evanescent. Using the sheath boundary condition, it is shown that for sufficiently close limiters, the slow wave couples to a sheath plasma wave and is no longer evanescent, but radially propagating. A self-consistent calculation of the rf-sheath width yields the resulting sheath voltage in terms of the amplitude of the launched SW, plasma parameters and connection length.

Keywords: fusion, rf-heating, sheaths, slow wave, scrape-off-layer.
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INTRODUCTION

It is well known that ICRF sheath interactions with walls and limiters can be responsible for sputtering, impurity generation, and parasitic power loss, as reviewed in Refs. 1 and 2. RF sheaths are generated primarily by the $E_{||}$ component (parallel to the background magnetic field B) and, in ICRF heating, are therefore associated with the slow wave (SW). The SW can arise near material boundaries by several mechanisms. In some situations the fast wave (FW) can access the wall, e.g. due to scrape-off-layer (SOL) propagation [3] or poor central absorption. It was shown [4,5] that when flux surfaces do not match the wall shape, the boundary conditions (BCs) require generation of the SW.

In the present paper, we consider the case where the SW is generated at the plasma-facing surface of the antenna and is free to propagate (or evanesce) into the SOL, dominantly along field lines, as suggested by several experiments. [6-8] Since our purpose is to gain conceptual insight into the underlying physics, we restrict our attention here to simple rectangular geometries with a constant density SOL. We model the localized SW source as a small aperture which emits waves into a box (the SOL), and study their spreading, evanescence and propagation. A numerical solution of wave propagation and sheath interaction with the SOL and plasma boundaries in more realistic geometry is also in progress. [9]

In previous work [10] we studied the propagation of SW resonance cones into a tenuous magnetized plasma, $\omega>\omega_{lh}$. The resonance cones interact with, and reflect from, the plasma sheath near a conducting wall. The fraction of launched voltage in the resonance cones that is transmitted to the sheath has a sensitive threshold-like turn-on, which controls the onset of strong and potentially deleterious rf-wall interactions in a tokamak. Here, we extend the work to "dense" SOL plasmas, $\omega<\omega_{lh}$, where the usual slow wave is evanescent, but due to sheath interaction we will see the SW can still propagate.

SLOW WAVE EIGENFUNCTIONS

For simplicity we consider SW modes even in $E_{||}(z)$ about z = 0 where z is parallel to B. The local SW dispersion relation in the plasma is

$$n_x^2 = \frac{\varepsilon_{||}}{\varepsilon_{\perp}}(\varepsilon_{\perp} - n_z^2) \quad (1)$$

and we invoke the sheath BC at the walls z = ± L, so that at z = L we have [4, 11]

$$E_x = -ik_x \Delta\varepsilon_{||} E_z \quad (2)$$

where x is radial (increasing towards the plasma core, x = 0 is the antenna SW source) and y is ignorable. Here $\mathbf{k} = k_x\mathbf{e}_x + k_z\mathbf{e}_z$ is the wavenumber, Δ is the width of the rf-sheath, (modeled as a thin vacuum layer) and $\varepsilon_{||} = 1 - \omega_{pe}^2/\omega^2$ is the parallel plasma dielectric. Eqs. (1), (2) and the polarization E_x/E_z determine a global dispersion relation which gives the SW eigenfunctions of the box, accounting for sheath BCs, viz.

$$\eta \tan\eta = (\eta^2 + b^2)\Lambda \quad (3)$$

where $\eta = k_z L$, $b^2 = -\varepsilon_{\perp}\eta_0^2$ with $\varepsilon_{\perp} = 1 - \omega_{pi}^2/(\omega^2 - \Omega_i^2)$, $\eta_0 = \omega L/c$ and

$$\Lambda = -\frac{\Delta\varepsilon_{||}}{L} \quad (4)$$

Typical behavior of the roots of Eq. (3) is shown in Fig. 1. For the metal wall limit $\Lambda = 0$ the roots are at $\eta_m = m\pi$ (m = 0, 1, 2, …) so that E_x vanishes at the wall. In the opposite (insulating wall) limit $\Lambda = \infty$ the roots are at $\eta_m = m\pi/2$ (m = 1, 3, 5 …). For intermediate Λ the roots transition between these cases, but there is also a new root with pure imaginary η. This root is the sheath-plasma wave (SPW). [5, 12] Eigen-functions of the SPW are localized in z to the sheaths for Λ << 1 (since from Fig. 1, Im η>>1), and have the character of surface waves that exist because of the plasma-vacuum interface at the plasma boundary. They become global modes for $\Lambda \sim 1$.

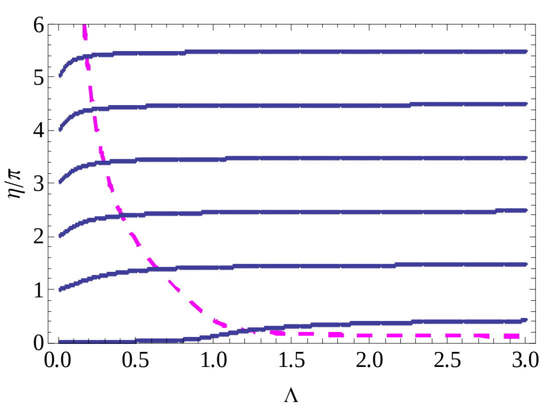

FIGURE 1. Roots of the global dispersion relation vs. sheath parameter Λ for the case b = 0.1. Real (solid), Im (dashed).

These eigenmodes form a complete set for the box that satisfy the sheath BCs in z and are chosen to be outgoing/evanescent waves in x.

PROPAGATION OF A LOCALIZED SW SOURCE

We project a Gaussian source of width *a* ($\sim\exp[-z^2/2a^2]$) onto the basis set to determine its propagation characteristics in x. It can be easily shown from Eq. (1) that for b >> 1, all the basis set functions evanesce on the scale of the electron skin depth $\delta_e = c/\omega_{pe}$ and that a localized source does not spread much in z before it decays in x. Consequently for b >> 1 the SW fields do not reach the wall, and there is no sheath interaction. However, for b < 1, which typically requires $L < \delta_i \equiv c/\omega_{pi}$ there is spreading in z, evanescence in x, and importantly, coupling to a mode which *propagates* in x, the SPW.

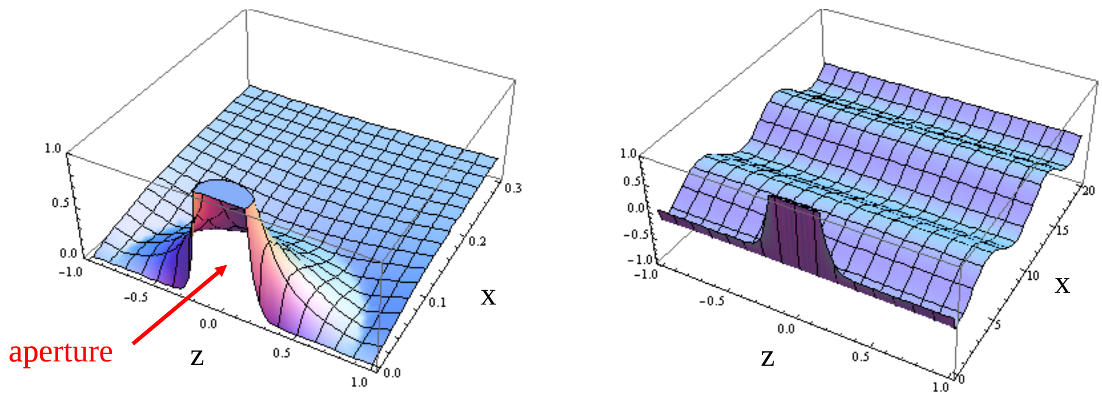

FIGURE 2. Field pattern and emergence of the SPW for specified Λ. Left: $|E_z(x, z)|$ for b = 0.1 and Λ = 3. The scale in z is normalized to L and the scale in x = (0, 0.3) is normalized to δ_e. Right: Re $E_z(x, z)$ for the same case, but with x shown over the range x = (0, 30) to show the propagating SPW.

The short scales in z spread in z but evanesce rapidity in x, on a scale $x \sim (m_e/m_i)^{1/2}L$. Long scale structures in z act on the $x \sim \delta_e$ scale and behave differently. In particular there is coupling to the SPW eigenfunction.

For b << 1, and Λ > 1, Eq. (3) yields the imaginary root as $\eta = ib[\Lambda/(\Lambda-1)]^{1/2}$ which is associated with the Alfvén mode in the limit $\Lambda \to \infty$, i.e. $k_z^2 v_a^2 = \omega^2/[1-(\omega/\Omega_i)^2]$. Normally, Alfvén resonance occurs for real k_z and $\omega < \Omega_i$. Here, $\omega > \Omega_i$ but imaginary k_z is allowed because of the finite domain and the sheath BCs.

Solutions for specified Λ are not generally self-consistent because the sheath width Δ must be determined from the Child-Langmuir law and the fields at the sheath entrance. Self-consistency is achieved when

$$\Delta = \lambda_{de}\left|\frac{\alpha e V_{sh}}{T} + \alpha_{th}\right|^{3/4} \quad \text{and} \quad V_{sh} = \Delta\varepsilon_{\|} E_z(z = L) \tag{5}$$

where the latter comes from matching $\varepsilon_{\|}E_z$ across the sheath-plasma interface. Here α and α_{th} are order unity factors (nominally $\alpha \sim 0.6$, $\alpha_{th} \sim 1$ to 3) which describe respectively the rectification of rf to dc voltages, and the thermal (Bohm) sheath. Solving Eqs. (5) for Δ or Λ, one can determine the sheath voltage for given b and reference value $\Lambda_0 = -(\lambda_{de}\varepsilon_{\|}/L)(\alpha e V_0/T)^{3/4}$ which effectively specifies the rf amplitude of the source voltage V_0. Results are shown in Fig. 3. Strong amplification of V_0 is possible for b << 1 near SPW resonance at $\Lambda \sim 1$, analogous to effects seen in Ref. 5. As b increases to order unity, V_{sh} decreases and the resonant structure and multiple roots disappear. Analogous to the resonance cone case [10] there is a critical Λ_0 at which the sheath goes from thermal to rf dominated.

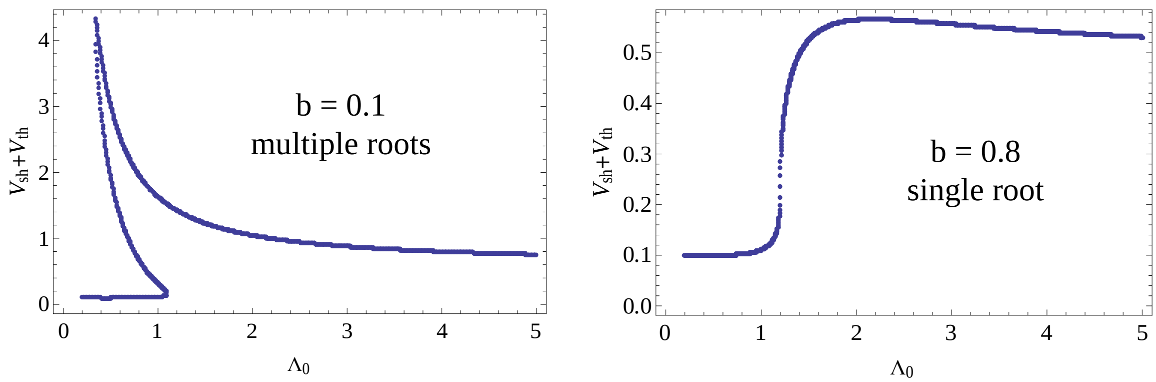

FIGURE 3. Self-consistent sheath voltage at large x from the SPW. The voltage appearing across the sheath V_{sh} is normalized to V_0 and the normalized thermal (Bohm) sheath voltage is $V_{th}/V_0 \equiv \alpha_{th}T/(\alpha eV_0) = 0.1$.

CONCLUSIONS

SW fields emitted by a localized source (antenna) propagate and evanesce into the SOL. SW interaction with wall sheaths is possible in some parameter regimes: tenuous plasmas [10] and dense plasmas with nearby limiters, typically $L_{\|} < \delta_i$. The coupling mechanism involves the sheath-plasma wave which can carry fields and sheath voltages radially into the plasma along metal surfaces.

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