

On the linear stage of thermal parametric instabilities in the ionosphere excited by HF pumping near electron gyroharmonics

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Abstract

Thresholds and growth rates of the thermal parametric instability in the ionosphere were studied taking into account the regular inhomogeneity (altitude dependence) of the plasma density and of the magnetic field strength. A noticeable decrease of the pump wave threshold power and an increase of the growth rate occurs when f_0 approaches the double resonance frequency $f_d = n f_{ce}(z_d) = f_{UH}(z_d)$, z_d being the altitude for double resonance. Particularly, the threshold power decreases relative to the non-resonant case by a factor 3–7 at $|f_0 - f_d(z_d)| \lesssim 15$ kHz for $n = 3$ and up to a factor 3 for $n = 4$. The instability growth rate can increase with a factor of 10^3 – 10^4 relative to the non-resonant case. The decrease of the threshold and increase of the growth rate occur for quite small scales of the striations, $l_\perp \sim 1$ m for $n = 3$ and $l_\perp \sim 0.5$ m for $n = 4$.

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1. Introduction

Many phenomena occurring in the ionospheric F region under the action of powerful HF radio waves are related to the excitation of small scale field aligned irregularities of plasma density (striations) and upper hybrid (UH) or electron Bernstein (EB) waves. In the presence of the strong electric field in the HF radio wave, these striations and UH waves appear due to the development of the thermal parametric instability, TPI, (Grach and Trakhtengertz, 1975; Dimant, 1977; Istomin and Leyser, 1998). The striations appear as a result of electron heating by the beating of the electromagnetic wave (pump wave) and seed plasma (UH) waves and the ensuing expulsion of plasma from the heated regions. In turn,

two UH waves (both the Stokes and anti-Stokes components) appear and amplify due to scattering of the pump wave off the striations. For a homogeneous medium, the electric field threshold for the TPI is much lower than the threshold for the pondermotive parametric instability, $E_{th,TPI}^2/E_{th,PON}^2 \sim \delta$, where $\delta \ll 1$ is the fraction of energy lost for an electron under a collision with a heavy particle (ion or neutral). Since the ionospheric plasma is inhomogeneous, the interaction between the pump wave, plasma waves, and striations occurs in a narrow region with size $l_m \approx (1/\pi)|d(k_0 - k_\parallel)/dz|^{-1/2}$ near the UH resonance level $\omega_0^2 \approx \omega_{UH}^2 = \omega_{pe}^2(z) + \omega_{ce}^2$, where the matching conditions

$$k_0(z) = k(z) \pm \kappa \quad (1)$$

are fulfilled. Here ω_0 , ω_{pe} and ω_{ce} are the pump wave, electron plasma and cyclotron frequencies, respectively, k_0 , k and κ are, respectively, pump wave, plasma wave, and striation wave vectors; z is the altitude. Notice that

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$l_m \ll L_T$, where L_T is the characteristic length of the striation along the magnetic field. This leads to an essential weakening of the interaction and an increase of the instability threshold compared to a homogeneous medium (Grach et al., 1978; Grach, 1979). In the nonlinear stage of the instability the heating of the plasma by beating plasma waves prevails over the pump–plasma wave heating, which provides an explosive character of the instability (resonance instability, Vas'kov and Gurevich, 1975, 1977) and also trapping of UH waves in striations becomes possible [see, e.g., Vas'kov and Gurevich, 1983; Gurevich et al., 1995; Mjølhus, 1993, 1998; Istomin and Leyser, 1998]. The nonlinear stage of the TPI, however, is beyond the scope of this paper.

It is well established (Leyser et al., 1994; Stubbe et al., 1994) that for pump frequencies close to a harmonic of the electron cyclotron frequency, $\omega_0 \approx n\omega_{ce}$, $n = 3-7$, the efficiency of the pump–plasma interaction is substantially weakened. This has been attributed to the appearance of “forbidden zones” both in configuration space and wave vector space for plasma waves with frequency ω close to the double resonance frequency $\omega_d = \omega_{UH} = n\omega_{ce}$, propagating across or almost across the geomagnetic field (Grach et al., 1994; Leyser et al., 1994). On the other hand, when ω lies further away from a gyroharmonic, a non-monotonic dependence of $|k|$ on z in the ionosphere can provide a significant increase in the interaction length l_m (see Grach et al., 1994; Leyser et al., 1994 and also Figs. 1 and 2). In the present paper, we study the characteristics of the threshold and the growth rate of the TPI in an inhomogeneous ionosphere for pump frequencies close to the ionospheric electron gyroharmonics.

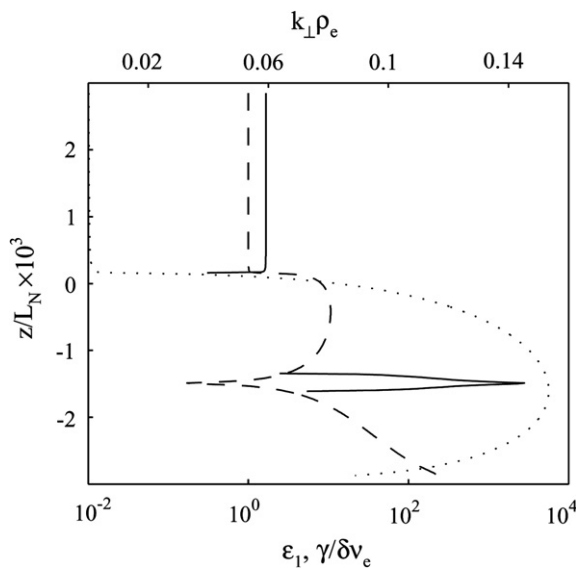


Fig. 1. Normalised threshold ε_1 (dashed line), growth rate $\gamma/\delta v_e$ (solid line), and $k_{\perp}\rho_e$ (dotted line) as a function of altitude. This plot is for the third harmonic, a frequency shift $\Delta f = +12$ kHz, and $\varepsilon_0 = 3$.

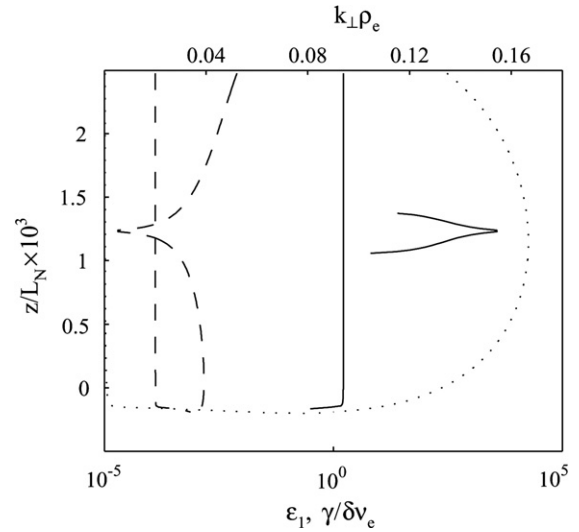


Fig. 2. Normalised threshold ε_1 (dashed line), growth rate $\gamma/\delta v_e$ (solid line), and $k_{\perp}\rho_e$ (dotted line) as a function of altitude. This plot is for the third harmonic, a frequency shift $\Delta f = -12$ kHz, and $\varepsilon_0 = 3$. The two branches are due to the fact that Eq. (4) has two roots for $\Delta f < 0$.

2. Theory

The initial (linear) stage for the TPI in an inhomogeneous ionosphere is described by a set of coupled equations for high frequency (UH or EB waves) and low frequency perturbations (striations). For the low frequency perturbations of the plasma density n and the temperature T we use the equations for the ambipolar diffusion and heat conduction (Gurevich, 1978)

$$\frac{\partial n}{\partial t} - \nabla \mathbf{D}_a \nabla n - k_T \frac{N}{T_e} \nabla \mathbf{D}_a \nabla T_e = 0, \quad (2)$$

$$\frac{\partial T_e}{\partial t} - \nabla \mathbf{D}_T \nabla T_e + \delta v_e T_e = Q, \quad (3)$$

where n is the low frequency plasma density, $\mathbf{D}_a$ the ambipolar diffusion tensor, $\chi_e = N \mathbf{D}_T$ the electron thermal conductivity tensor, k_T a dimensionless coefficient of order unity, N the plasma density, T_e the electron temperature, ν_e the collision frequency for electrons, and $Q = 2.3N(\mathbf{E}_0 \boldsymbol{\sigma}^e \mathbf{E})$ is the heating source due to the interaction between the electromagnetic pump wave $\mathbf{E}_0$ and the induced plasma waves $\mathbf{E}$. Here, $\boldsymbol{\sigma}^e$ is the Hermitian electron conductivity tensor.

The HF plasma waves are described by transport equations for slowly varying amplitudes of certain Fourier components – obtained in the geometrical optics approximation – with a source term related to the electromagnetic pump wave, scattering off the striations (for details, see Grach et al., 1978). The linear dispersion relation for HF plasma waves must be fulfilled in this approximation, and for a Maxwellian plasma and $k \gg \omega_0/c$, it is given by Alexandrov et al. (1984)

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