A Numerical Study of the Langmuir Parametric Instability Excited by Powerful HF Wave Heating at Different Latitudes

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Abstract

Parametric Decay Instability (PDI) plays an important role in the interaction of the high-power HF EM waves with ionosphere plasma. In this study, we have constructed a numerical simulation model for studying PDI with a nearly realistic ionosphere background and a radio wave propagation model by taking a proper processing for the routine dynamic equations of plasma with Generalized Zakharov method. The simulation results found that high-power HF EM waves could excite two electrostatic modes of a Langmuir wave and an ion acoustic wave near the reflection point of the ordinary wave (O-mode) within a timescale order of millisecond. The wave number of the two electrostatic modes in the simulation is about 5-11 rad/m which is approximately consistent with the theoretical results 4-7 rad/m calculated by the dispersion relation. The amplitude of density perturbation grows exponentially and significantly influencing the plasma frequency related to 'low frequency' density background. This processes are also followed by plasma caviton structures and trapped Langmuir waves. The amplitude of electrostatic field in the perturbed space can reach to 100V/m. Finally, it leads to an intense localized cavitating turbulence. This paper also presents the simulation results of Langmuir parametric instability (LPI) excited by powerful HF wave heating at three latitudes. The study of this article contributes to formation of a deep impression for the physical mechanism of the Parametric Decay Instability (PDI). It is also helpful to research on the nonlinear interaction between the high-power HF EM waves and ionosphere plasma.

1. Introduction

Langmuir parametric instability is the most important physical process in the ionospheric heating experiments. Theory and observations show that a large number of phenomena are related to Langmuir parametric instability, including HF-enhanced plasma lines (HFPLs), stimulated electromagnetic emissions (SEEs), enhanced airglow, Langmuir turbulence and artificial field-aligned irregularities [1-3].

Both the pondermotive force and the pump wave are contributed to the excitation of the LPI. The electrostatic Langmuir wave and ion acoustic wave are excited and developed in a very short time (~ms scale). In addition, the development of the LPI is accompanied by the cascade process, which in consequence produce a group of Langmuir spectra [4-7]. The saturated spectra determine the final state of the plasma in the heating region.

Although LPI has been investigated in a number of studies, there are relative few studies devoted to the LPI excitation in middle and low latitudes, where the magnetic field has a significant dip angle. Recent studies of LPI excitation by [8, 9] have revealed that there is specific different physical processes which dominate in different latitude.

In this study, we utilize a generalized Zakharov model to investigate the LPI excitation and evolution by powerful HF wave heating at different latitudes. By using the simulation results, we try to understand the physical processes for the LPI excitation and the effects of the magnetic field.

2. Simulation Model

The simulation model is based on a generalized Zakharov model [4-6]. This model is one-dimensional geometry and along the z-axis. The high and low frequency perturbations are solved in two different grids.

Three simulations are carried out in this study. The simulated heating experiments are selected at three locations, namely Tromsø (dip angle 78º), Wuhan (dip angle 45º) and Sanya (dip angle 18º), which represent the high, middle and low latitudes. The heating frequency is 6 MHz. Accordingly, the reflection height for high, middle and low latitude is about 275.3 km, 245.5 km and 252.5 km, respectively.

Background ionospheric parameters are adopted from international reference ionosphere model (IRI-2012) [10]. The total simulation region is from 250 km to 300 km. The small-scale structures are calculated in a dense grid with 4 cm resolution, which ranges from 272.8 km to 275.8 km for high latitude, from 241.8 km to 245.8 km for middle latitude and from 249 km to 253 km for low latitude.

3. Results

Figure 1 presents the time evolution of electron density perturbations at reflection region at Tromsø from t = 0 to t = 6.5 ms. For high latitude case, the Langmuir density perturbations are firstly excited at about t =1 ms and very close to the reflection height. As the perturbation develops, the excitation of LPI tends to be descendent to lower height. At t = 6.5 ms, the strongest perturbation is about 1 km lower than the reflection height.

Figure 2 and 3 present the simulation results of time evolution of perturbations at middle (Wuhan) and low latitude (Sanya). Similar perturbations due to the LPI excitation and development can also be observed. However, by comparing to the results presented in Figure 1, different features in Figure 2 and 3 can be found. The perturbations appear at t = 2.6 ms in Figure 2 and at t = 5.0 ms in Figure 3, which is later than Figure 1. At t = 6.5 ms, the strongest perturbation is much lower than the reflection height.

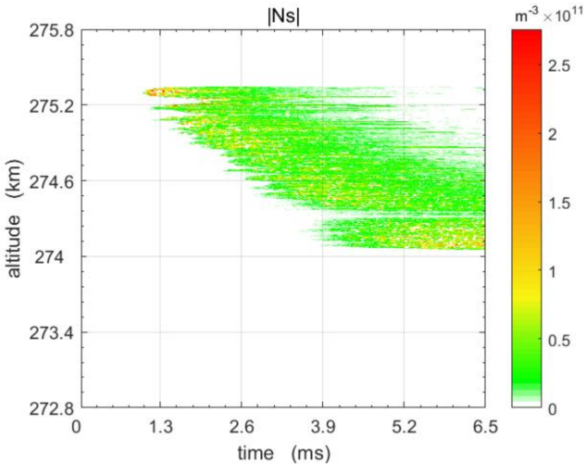

Figure 1. Simulation results of time evolution of electron density perturbation at high latitude, Tromsø (dip angle 78º).

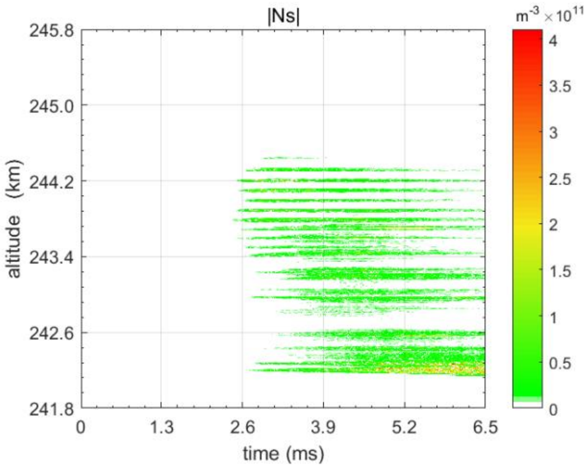

Figure 2. The same format with Figure 1, but at middle latitude, Wuhan (dip angle 45º).

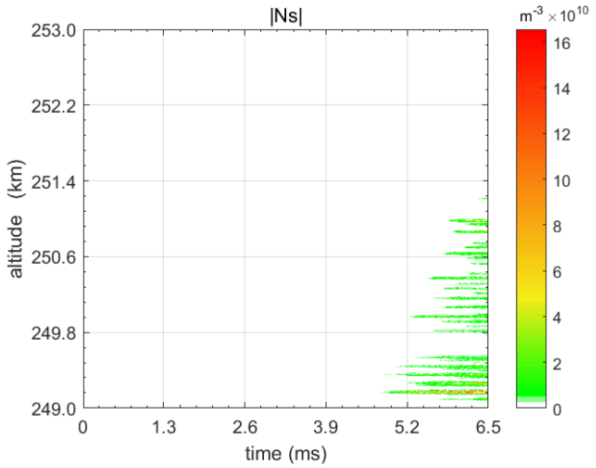

Figure 3. The same format with Figure 1, but at low latitude, Sanya (dip angle 18º).

4. Discussion and Summary

We have performed a simulation investigation on the Langmuir parametric instability based on a generalized Zakharov model. Three different cases of the Langmuir parametric instability excited at different latitude indicate that the background magnetic dip angle is important for LPI excitation. The LPIs excited at middle and low latitude are quite different from that of high latitude.

5. References

1. C. Zhou, B. Ni, X. Wang, M. Liu, X. Xu, C. Wang, R. Shi, X. Gu, Y. Zhang, and Z. Zhao, "A numerical study of large-scale ionospheric modulation due to the thermal process by powerful wave heating," *Journal of Geophysical Research*, 121, 2016, doi: 10.1002/2016JA022355.

2. X. Wang, P. Cannon, C. Zhou, F. Honary, B. Ni, and Z. Zhao, "A theoretical investigation on the parametric instability excited by X-mode polarized electromagnetic wave at Tromsø," *Journal of Geophysical Research*, 121, 2016, pp. 3578–3591, doi: 10.1002/2016JA022411.

3. X. Wang, C. Zhou, M. Liu, F. Honary, B. Ni, and Z. Zhao, "Parametric instability induced by X-mode wave heating at EISCAT," *Journal of Geophysical Research*, 121, 2016, pp. 10,536–10,548, doi: 10.1002/2016JA023070.

4. B. Eliasson, and B. Thidé, "Zakharov simulation study of spectral features of on-demand Langmuir turbulence in an inhomogeneous plasma," *Journal of Geophysical Research*, 113, A02313, 2008, doi: 10.1029/2007JA012491.

5. B. Eliasson, and L. Stenflo, "Full-scale simulation study of the initial stage of ionospheric turbulence," *Journal of Geophysical Research*, 113, A02305, 2008, doi: 10.1029/2007JA012837.

6. B. Eliasson, and K. Papadopoulos, “HF wave propagation and induced ionospheric turbulence in the magnetic equatorial region,” *Journal of Geophysical Research*, 121, 2016, pp. 2727–2742, doi: 10.1002/2015JA022323.

7. S. Kuo, “Ionospheric modifications in high frequency heating experiments,” *Physics of Plasmas*, 22, 012901, 2015, doi: 10.1063/1.4905519.

8. B. Eliasson, and K. Papadopoulos, “HF wave propagation and induced ionospheric turbulence in the magnetic equatorial region,” *Journal of Geophysical Research*,, 121, 2727-2742, doi: 10.1002/ 2015JA022323.

9. H. C. Carlson, F. T. Djuth, and L. D. Zhang, “Creating space plasma from the ground,” *Journal of Geophysical Research*, 122, 2016 doi: 10.1002/2016JA023380.

10. D. Bilitza, L. A. McKinnell, B. Reinisch, and T. Fuller-Rowell, “The International Reference Ionosphere (IRI) today and in the future,” *Journal of Geodesy*, 85, 2011, pp. 909-920, doi: 10.1007/s00190-010-0427-x.