NUMERICAL SIMULATIONS OF A THREE-WAVE COUPLING OCCURRING IN THE IONOSPHERIC PLASMA

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1. Introduction

In the Solar Power Satellite (SPS) project, the solar energy is converted to microwaves and transmitted to the ground. Previous rocket experiments revealed that the nonlinear interaction between intense microwaves and the ionospheric plasma excites electrostatic waves at frequency around the local plasma frequency, which may cause the energy loss of the microwave. Theoretical analysis showed that the excited electrostatic waves is due to so called three-wave coupling. In order to clarify the nonlinear process, a microwave active experiment is planned with the JEM exposed facility in the international space station. Prior to the experiment we performed numerical simulations with a PIC (Particle-In-Cell) model. In the simulations, we focus on the spatial and temporal evolution of the three-wave coupling as well as the dependence of the interaction on the amplitude of the pump electromagnetic waves.

2. Simulation model

The mode-coupling equations describe the temporal variation of the three-wave coupling. To see the spatial variation as well as the temporal one, we performed one-dimensional numerical simulations with the following model. Instead of setting a pump wave uniformly in the simulation system, we emit electromagnetic waves from an antenna placed at one side of the simulation boundary into magnetized plasma. In the present case, we put the external magnetic field along the 1D system for simplicity. In reality, we utilize the frequency of GHz order for the pump wave while the plasma frequency of the ionospheric plasma and the electron cyclotron frequency are around is around M(k) Hz. In the present simulations, however, we reduce the frequency ratio between the pump wave and the plasma characteristic ones to save the computational time. We set the plasma frequency and the frequency of the pump wave as 4.0 and 13.2, respectively by assuming the electron cyclotron frequency is unity.

3. Simulation results

Figure 1 shows a $\omega - k$ diagram obtained by taking Fourier transformation of EM and ES field data in space and time where ω and k denote frequency and wave number, respectively. In the theory of the three-wave coupling for Raman-scattered type, intense electromagnetic waves whose

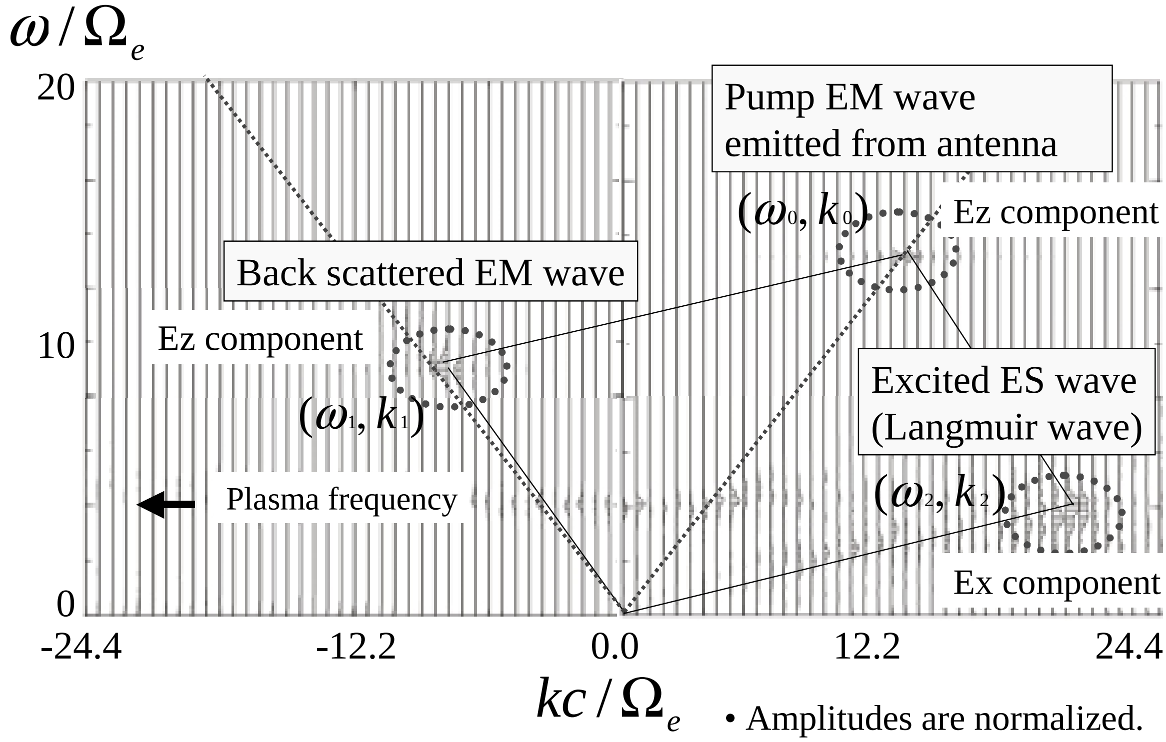

Fig.1 $\omega - k$ diagram obtained by taking Fourier transformation of EM and ES field data in space and time where ω and k denote frequency and wave number, respectively.

frequency and wave number are ω_0 and k_0 respectively cause backscattered waves with ω_1 and k_1 and electrostatic waves with ω_2 and k_2. In the above coupling the total energy and momentum should be conserved. Namely, $\omega_0 = \omega_1 + \omega_2$ and $k_0 = k_1 + k_2$ should be satisfied, respectively. In the figure the obtained wave spectrum is plotted at each wave number with normalized amplitude. The dashed lines correspond to the speed of light. It is found that a fraction of the pump wave (ω_0, k_0) is backscattered (ω_1, k_1) and low-frequency ES wave (ω_2, k_2) is excited around the local plasma frequency with satisfying the relation of the three-wave coupling.

Figure 2 shows profiles for the pump electromagnetic and excited electrostatic waves and the electron temperature. The vertical and horizontal axes show the normalized time and the distance from the antenna location, respectively. In panel (a), we see the pump waves propagating away from the antenna with the speed of light. Note that the intensity is not constant around time periods of 10.24 - 15.36 and 20.48-25.6. The modulation of the pump amplitudes is due to the wave-wave interactions triggered by the three-wave coupling. In panel (b), as clearly shown around the time 10.24 - 20.48, electrostatic (ES) waves are excited due to the three-wave coupling. The profile shows that the propagating velocity is much less than the speed of light After the time 25.6, the profiles show complicated structure. In panel(c), the electron temperature increases as shown around the time 20.48 in accordance with the excitation of the ES waves.

Figure 3 indicates detailed analysis of the ES wave excitation. The panels focus on the first and second three-wave coupling. The first coupling starts to occur around the time 10.24. The interesting feature we should mention is that the region of the ES wave excitation is limited up to 3 from the

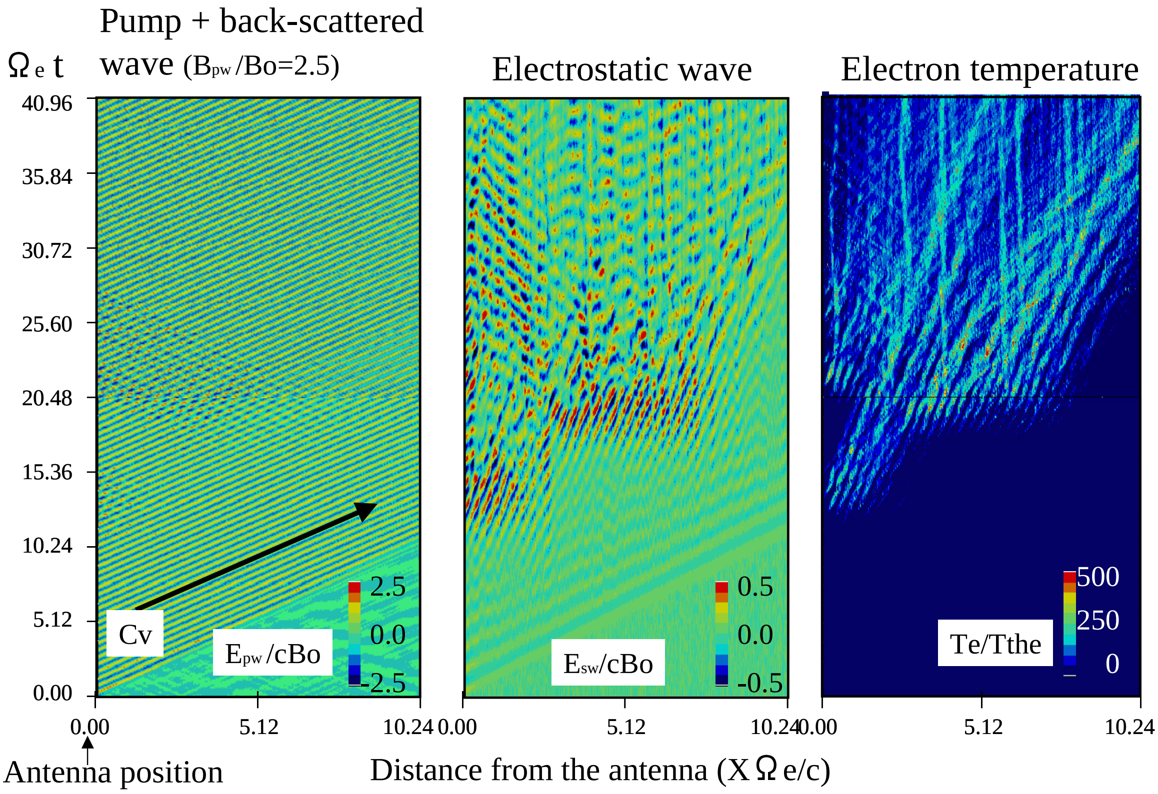

Fig.1 Profiles for the pump electromagnetic and excited electrostatic waves and the electron temperature

antenna location. Beyond this region, no waves are excited until the time 15.36. Once the three-wave coupling starts to occur, a part of the pump waves are backscattered and ES waves are excited. Around this time, pump waves cannot penetrate with enough intensity to trigger the coupling beyond the region. Corresponding the ES wave excitation, electrons are locally heated as shown in panel (b). The ES wave is the Langmuir wave whose dispersion relation depends on the plasma temperature. As the local temperature increases, the dispersion relation is modified and does not satisfy the relation of the three-wave coupling. Then the coupling ceases as shown at the time around 15.36. Correspondingly, the heated electrons are diffused and the increase of the temperature also stops. The second three-wave coupling is now ready to occur because the pump wave can fully propagate through the system. Since the plasma condition at the region where the first three-wave coupling occurred has already been modified by the ES waves, the second coupling tends to occur at a spatial region around 3-6 which is beyond the first region. As shown in the first interaction, the ES waves are strongly excited and they propagate with the phase speed of the Langmuir waves. Correspondingly, the electron temperature also increases at the region where the ES waves are intense. As to the wave energy transmission through the system, it is found that approximately 80 % of the pump energy reaches at the end of the simulation system.

Although not displayed, the dependence of the ES waves on the intensity of the pump waves is examined. From the mode-coupling equations, we can obtain the temporal growth rate of the ES waves, which is proportional to the intensity of the pump EM waves. We performed the computer experiments with different amplitude of the pump waves and could qualitatively confirm the above

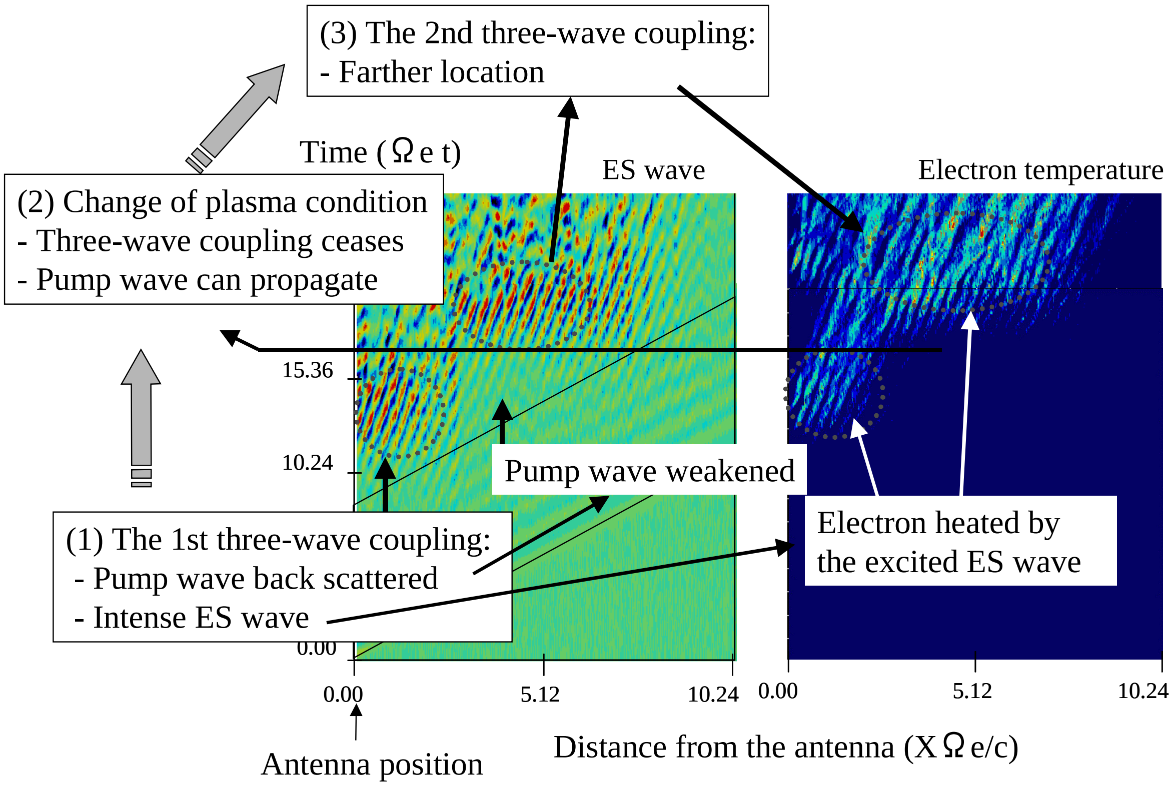

Fig.1 Detailed analysis of the ES wave excitation for the first and second three-wave coupling.

relation.

4. Summary

In order to study the nonlinear wave-wave-particle interaction associated with the microwave energy transmission in space plasmas, we perform one-dimensional simulations with the PIC model. In the simulation space filled with magnetized plasma, we emit intense electromagnetic waves from an antenna located at one edge of the simulation system. When the electromagnetic waves are intense enough, a three-wave coupling occurs, which is the consequence of a nonlinear interaction between forward and backward propagating high-frequency electromagnetic waves and a low-frequency electrostatic one propagating in the forward direction. The results show that a fraction of the electromagnetic waves emitted from the antenna is backscattered by the background plasma, which induces electrostatic waves at the plasma frequency. Since the electrostatic waves cause electron heating, the local plasma condition changes and the three-wave coupling ceases. When the heated electrons escape from the antenna region along the magnetic field, the background plasma recovers the initial conditions, and the three-wave coupling starts again. As to the wave energy transmission through the system, it is found that approximately 80 % of the pump energy reaches at the end of the simulation system with the present simulation model.

Reference

Matsumoto, H., et al., , Computer Simulation on Nonlinear Interaction of Intense Microwave with Space Plasmas, Electronics and Communications in Japan, Part 3, 78, 89-103, 1995.