# 2D Particle-in-cell Simulations for ESW Research in Space Plasma

## Section III Results

Two-dimensional (2D) electrostatic particle-in-cell simulations were performed to investigate the nonlinear evolution of electron bi-stream instability in weakly ($\Omega_e = 0.5\omega_{pe}$ , where $\Omega_e$ and $\omega_{pe}$ were the electron frequency and electron plasma frequency, respectively) and strongly ($\Omega_e = 2\omega_{pe}$) magnetized plasma.

### 3.1 What can be found in the weakly magnetized plasma?

Figure 1(a) and (b) showed the contour graphs of $E_x$ and $E_y$ in the weakly magnetized plasma at different time respectively. Similar to the 1D model, nearly monochromatic electrostatic waves were firstly excited. The wavelength of these waves was about $20\lambda_D$, and the dispersion relation of then was $\omega = \frac{1}{2}kV_d$ approximately. With the increase of the amplitude of these waves, the nonlinear dynamic effects were represented. As the Figure of the electric field at $\omega_{pe}t = 24$ showed, these waves coalesced with adjacent waves and the structures on the perpendicular direction became regular. At last one or several solitary waves were formed, as the Figure of the electric field at $\omega_{pe}t = 297$ showed.

From the Figure 2, it was easy to find that the parallel cut of the parallel electric field ($E_x$) exhibited bipolar structures while the perpendicular electric field ($E_y$) was unipolar, which was in accord with Umeda [Umeda et al., 2006]. However, these 2D electrostatic structures would disappear in future. And in the Figure 3, the electron phase-space holes could be found in both beam electrons and background electrons, which were correspond to the electrostatic structures.

## 3.2 Case 2 (in the strongly magnetized plasma)

Figure 4(a) and (b) showed the contour graphs of $E_x$ and $E_y$ in the strongly magnetized plasma at different time respectively. It was the same with the phenomenon in the weakly magnetized plasma firstly. But in the strongly magnetized plasma, the electron holes and the electrostatic structures were quasi-one-dimensional, that is to say, the parallel extent was limited while the perpendicular extent was unlimited.

However, as an innovation, it was found that on the direction which was perpendicular to the background magnetic field, it was vicissitudinous in both parallel and perpendicular electric field. The electrostatic structures as Figure 5 showed were instable. They can excited electrostatic whistler waves, which were nearly perpendicular to the background magnetic field and could destroy the electrostatic solitary structures.