§3. Particle Acceleration by a Collisionless Shock Wave and Associated Instabilities

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Using theory and two-dimensional particle simulations, we have studied formation of collisionless shock waves in a magnetized plasma, ultrarelativistic electron acceleration by an oblique shock wave, and finite beta effects on magnetosonic waves in a two-ion-species plasma.

(1) Formation processes of collisionless shock waves

Particle simulations have revealed that a magnetosonic shock wave can rapidly accelerate particles with various mechanisms$^{1)}$. However, formation processes of shock waves have not been fully understood. We have studied shock formation due to interactions between exploding and surrounding plasmas and evolution of modified two-stream instabilities using a 2D (two spatial coordinates and three velocity components) electromagnetic particle code with full ion and electron dynamics$^{2,3)}$.

An external magnetic field is in the z direction and the initial fluid velocity of the exploding plasma is $\boldsymbol{v}_0 = (12v_{\rm A}, 0, 0)$, where $v_{\rm A}$ is the Alfvén speed. The simulation plane is (x, z). Figure 1 shows the contour map of $\bar{B}_z$ in the (x, t) plane, where $\bar{B}_z$ is the z-averaged B_z. $x_{\rm iEb}$ is the averaged trajectory of ions that were initially at the front of the exploding plasma, while $x_{\rm iSb}$ is for ions that were at the end of the surrounding plasma. Exploding and surrounding electrons do not mix because they move with $\boldsymbol{E} \times \boldsymbol{B}$ drift. In the early stage, the exploding ions penetrate the surrounding ions and are decelerated because of the $\boldsymbol{v} \times \boldsymbol{B}$ force. This intensifies $\bar{B}_z$ in the region $x_{\rm eb} < x < x_{\rm iEb}$, and a strong magnetic-field pulse forms. At $\Omega_{i0}t \simeq 1$, this pulse splits into two pulses, which then develop into shock waves, one propagating forward away from $x_{\rm eb}$ and the other backward. This splitting is caused by ion reflection.

In the region $x_{\rm iSb} < x < x_{\rm iEb}$, relative cross-field motion between ions and electrons can excite modified two-stream instabilities through interactions with whistler waves. The instabilities evolve in the magnetic field that is being gradually compressed. Because of the nonlinear evolution of the instabilities, 2D fluctuations grow to large amplitudes in the strong magnetic-field pulse region. Figure 2 shows ion phase-space plots of surrounding and exploding ions, the x profile of $\bar{B}_z$ and the contour maps of the 2D fluctuation of B_z, $\delta B_z = B_z - \bar{B}_z$, in the (x, z) plane at $\Omega_{\rm i0}t = 0.875$. The amplitudes of δB_z are noticeably large near the position where $\bar{B}_z$ has a steep slope. The 2D fluctuations of B_z influence the ion reflection and the structure of generated two pulses.

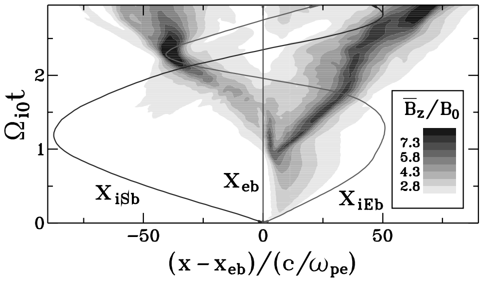

Fig. 1: Contour map of z-averaged B_z in the (x, t) plane.

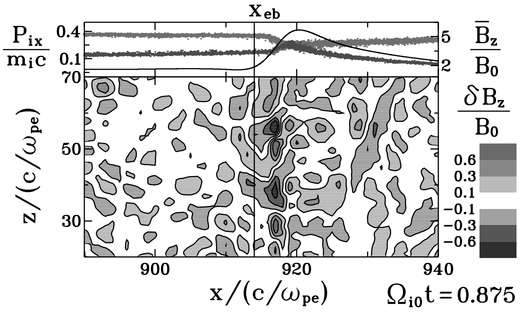

Fig. 2: Ion phase-space plots, x profile of $\bar{B}_z(x)$, and contour map of δB_z in the (x, z) plane, at $\Omega_{\rm i0}t = 0.875$.

We also performed simulations for various values of v_0 and of the angle between $\boldsymbol{v}_0$ and $\boldsymbol{B}_0$. We discussed the parametric dependence of the properties of generated two pulses and of magnetic fluctuations$^{4)}$.

(2) Electron acceleration by an oblique shock wave

Using 2D relativistic electromagnetic particle simulations, we studied electron trapping in an oblique shock wave, detrapping due to 2D electromagnetic fluctuations, and subsequent acceleration to higher energies. We showed the dependence of the electron motions on the propagation speed and angle of the shock wave$^{5)}$.

(3) Theory for nonlinear magnetosonic waves

We extended nonlinear theory for high- and low-frequency magnetosonic waves in a two-ion-species plasma to include finite beta effects$^{6)}$. We showed the condition for KdV equation to be valid and then discussed the beta dependence of collisionless damping of the nonlinear high-frequency-mode pulses due to heavy ion acceleration.

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