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

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We have studied the propagation of nonlinear magnetosonic waves and associated particle acceleration in a collisionless plasma: specifically, (1) effects of electromagnetic fluctuations on electron motions in an oblique shock wave, (2) finite beta effects on magnetosonic waves in a two-ion-species plasma, and (3) formation of forward and backward shock waves in a magnetized plasma.

(1) Electron acceleration by an oblique shock wave

A magnetosonic shock wave propagating obliquely to an external magnetic field with a propagation speed $v_{\rm sh} \simeq c\cos\theta$, where θ is the propagation angle of the shock wave, can trap and accelerate electrons to ultra-relativistic energies.[1] These electrons can excite electromagnetic fluctuations along the shock front through whistler wave instabilities, which we call 2D fluctuations. The effects of the 2D fluctuations on electron motion are investigated in detail.[2,3] First, the evolution of a large number of electrons is analyzed with a 2D (two spatial coordinates and three velocity components) electromagnetic particle code, for which a shock wave is assumed to propagate in the x-direction in an external magnetic field in the (x, z) plane. We call these electrons 2Ds electrons. Next, we calculate the motion of the same number of test electrons in the y-averaged electromagnetic fields obtained from the 2D electromagnetic particle simulation. That is, in the equation of motion of the test electrons, the 2D fluctuations are excluded. We denote the test electrons as 1Dt electrons.

Figure 1 shows the phase space plots (x, γ) of 2Ds and 1Dt electrons, where γ is the Lorentz factor. Some 1Dt electrons are trapped and energized in the main pulse region, and there are no energetic electrons outside the region. However, energetic 2Ds electrons exist in a wider region from the upstream region to the downstream region. The maximum γ of 2Ds electrons is higher than that of 1Dt electrons.

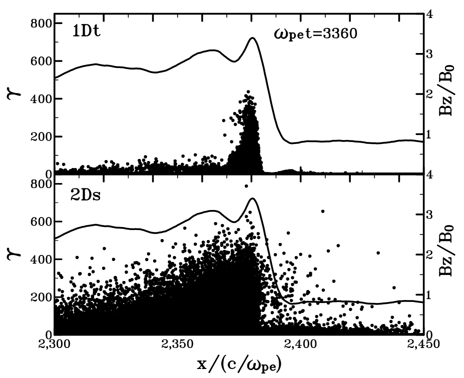

Fig. 1: Phase space plots of 1Dt and 2Ds electrons.

Figure 2 shows the time variations in γ and x of a 2Ds electron (black solid line) and a 1Dt electron (gray dashed line). Although the initial velocities and positions of the 2Ds and 1Dt electrons are exactly the same, their orbits are completely different. The 1Dt electron continues to be trapped in the main pulse until the end of the simulation run, whereas the 2Ds electron is detrapped from it to the upstream region. The γ of the 1Dt electron oscillates with time, whereas the γ of the 2Ds electron increases continuously on average. THis shows that the 2D fluctuations can cause detrapping of energetic electrons from the main pulse and their subsequent acceleration to much higher energies.

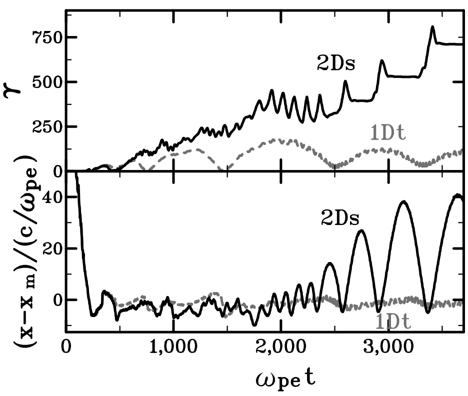

Fig. 2: Time variations in γ and x of 1Dt and 2Ds electrons.

(2) Theory for nonlinear magnetosonic waves

We have extended the nonlinear theory for magnetosonic waves in a two-ion-species plasma to include finite beta effects.[4] Heavy ion acceleration by the high-frequency mode pulse and wave damping due to this energy transfer have also been discussed.

(3) Collision of two magnetized plasmas

We have studied formation of forward and backward shock waves due to a collision of two plasmas in a magnetic field with a two-dimensional electromagnetic particle code.[5] Effects of modified two-stream instabilities on the shock structure have been investigated.

1) N. Bessho and Y. Ohsawa, Phys. Plasmas **6**, 3076 (1999).

2) M. Toida and J. Joho, J. Phys. Soc. Jpn. **81**, 084502 (2012).

3) M. Toida and J. Joho, Plasma and Fusion Res. **8** 2401031 (2013).

4) Y. Aota and M. Toida, Plasma and Fusion Res. **8** 2401018 (2013).

5) T. Uragami and M. Toida, submitted to Plasma and Fusion Res.