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Generation of Electromagnetic Waves and Alfvén Waves during Coalescence of Magnetic Islands in Pair Plasmas

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Abstract

We show that the strong magnetic flux can be generated during coalescence of magnetic islands in pair plasmas. It is also shown that the charge separation with a quadrupole-like structure is produced near the localized magnetic flux. There appear strong wave emissions with electromagnetic waves and Alfvén waves during the decay of the magnetic flux and the charge structure.

Keywords:

pair plasma, coalescence of magnetic islands, magnetic flux generation, electromagnetic wave, Alfvén wave

1. Introduction

Electron-positron (pair) plasmas are thought to be sources of intense electromagnetic radiation from many objects in space, such as pulsar magnetospheres, active galactic nuclei (AGN) and the early universe. It is well known that magnetic reconnection in plasmas is one of important energy conversion processes from magnetic field energy to plasma kinetic energy as well as high-energy particles. The coalescence instability [1] is an ideal magnetohydrodynamic (MHD) instability in which parallel currents attract each other and to coalesce into larger units through magnetic reconnection. A lot of works on the coalescence dynamics in electron-ion plasmas have been published both in MHD model and collision-less model. Pritchett [2] reported a new effect on the magnetic flux generation during coalescence of magnetic islands in electron-ion plasmas, and showed that during the nonlinear stage of the merging process of two magnetic islands, a quadrupole out-of-the-plane magnetic field structure with a size of the ion skin depth is formed. On the other hand, study on magnetic reconnection and coalescence dynamics [3] in pair plasmas has begun under some motivations in astrophysical plasmas.

In the present paper we show that the strong magnetic flux can be generated during coalescence of magnetic islands. Also we find that the charge separation with a quadrupole-like structure is produced from the localized magnetic flux generation. During the decay phase of the magnetic flux and the charge structure, there appear strong wave emissions of electromagnetic waves and Alfvén waves.

2. Simulation Results

The simulation code used here is 2-D fully relativistic electromagnetic particle-in-cell (PIC) code. Firstly, we show the simulation results for a thin current, of which width is order of electron skin depth. Next, we show the results for a thick current sheet with width of twice electron skin depth (See Fig.4).

Figures 1(a) and (b) show coalescence of magnetic islands at $\omega_{pe}t$ = 21.08 and $\omega_{pe}t$ = 31.62 in the *x*-*y* plane. Two magnetic islands formed by repeating coalescence of small magnetic islands develop finally to a single large island.

Figures 1(c) and (d) show the electron spatial distribution at $\omega_{pe}t = 21.08$ and $\omega_{pe}t = 31.62$ in the *x-y* plane. There are three clouds as seen in Fig. 1(c). As seen in Fig. 1(d), these clouds collide each other and become a single large cloud.

Figure 2 shows three snapshots of the magnetic flux B_z, the vector plots of magnetic field and the electric charge density at $\omega_{pe}t = 28.46$, 31.62 and 36.89 in the *x-y* plane. The left column shows the time development of the magnetic flux B_z. The middle column shows the vector plots of magnetic field $B_x - B_y$. The right column shows the spatial distribution of the electric charge density $(\rho_+ - \rho_-)$. As seen in Fig. 2(a-1) there is no magnetic flux before coalescence of magnetic islands. But the strong localized magnetic flux generation with a pair polarity is observed in Fig. 2(a-2). Recently Sakai et al. [4] investigated the generation mechanism of magnetic fields during collision of thin plasma clouds. Figure 2(a-3) shows that the magnetic flux can diffuse in space and decay. Also the charge separation with a quadrupole-like tructure is formed (See Fig. 2(c-2)) near the region of the magnetic flux generation. This charge structure corresponds to the region where B_z is negative. Figure 2(c-3) shows the decay of the charge structure.

Figure 3(a) shows the dispersion relation of the electric field E_y along the magnetic field B_x, which is obtained by performing a 2-D Fourier analysis of the field data taken in the *x*-direction on $y = 45\Delta$. We find that there occur the electromagnetic waves with high-frequency. Figure 3(c) shows the time history of the electric field energy E_y^2, which is obtained by performing the inverse Fourier transformation by use of the data of Fig. 3(a). As seen in Fig. 3(c), the electromagnetic waves can be generated after formation of the strong charge separation, and the emissions grow in the decay phase of the charge structure.

Figure 3(b) shows the dispersion relation of the magnetic field B_z along the magnetic field B_x. Fig. 3(d) shows the time history of the magnetic field energy B_z^2. There is strong emission with low-frequency, which branch corresponds to the Alfvén waves. Three solid

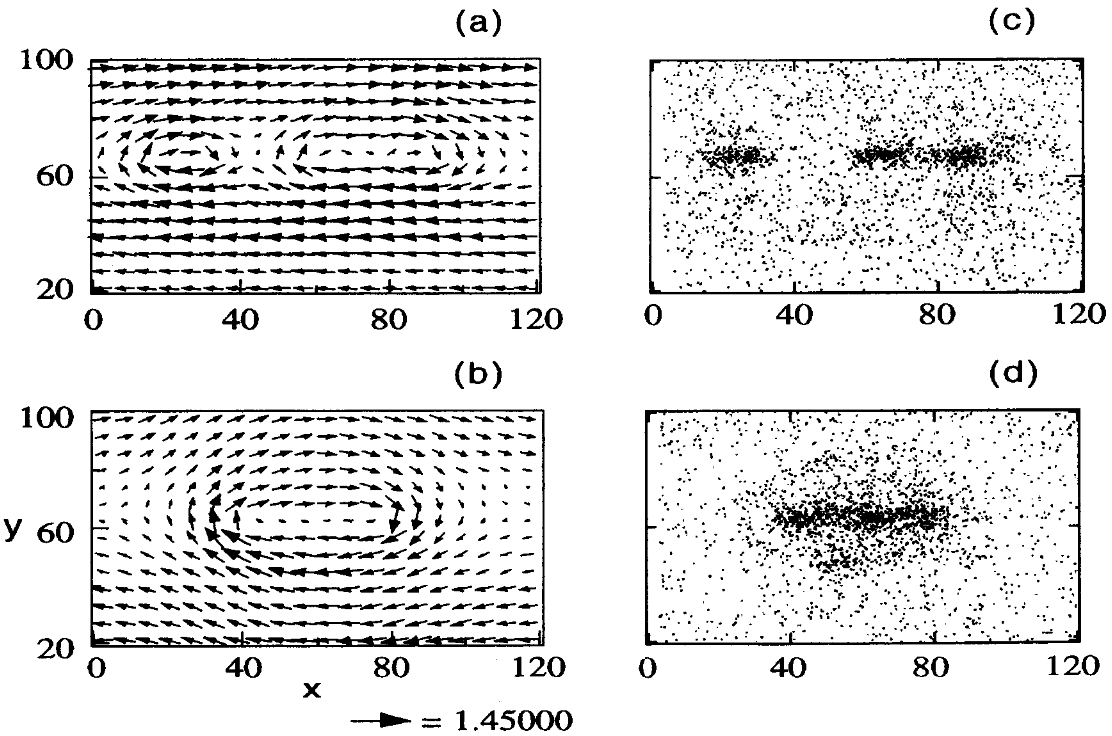

Fig. 1 For a thin current sheet with a width of electron skin depth, the vector plots of the magnetic field $B_x - B_y$ at (a) $\omega_{pe}t = 21.08$ and (b) $\omega_{pe}t = 31.62$ in the *x-y* plane. The electron spatial distribution at (c) $\omega_{pe}t = 21.08$ and (d) $\omega_{pe}t = 31.62$ in the *x-y* plane.

lines in Fig. 3(b) mean theoretical curves with (1) $\omega_{ce}/\omega_{pe} = 0.5$, (2) $\omega_{ce}/\omega_{pe} = 0.4$, and (3) $\omega_{ce}/\omega_{pe} = 0.3$, which are obtained from the dispersion relation of the Alfvén waves $\left(\frac{kc}{\omega}\right)^2 = 1 - \frac{2\omega_{pe}^2}{\omega^2 - \omega_{ce}^2}$. The strong emission in the simulation result is located between (1) and (2) in Fig. 3(b). We conclude that $\omega_{ce}/\omega_{pe} = 0.45$ is a reasonable value to fit the theoretical dispersion curve. Figure 3(d) shows that the Alfvén waves grow in the decay phase of the strong localized magnetic flux.

Figure 4 shows three snapshots of the same physical quantities as in Fig. 2 at $\omega_{pe}t = 36.89$, 42.16 and 47.43 for a thick current sheet with a width of twice electron skin depth. As seen in Fig. 4(a-1), the magnetic flux with different polarity appears lengthwise, because of wide width of a current sheet. The structure of the charge separation becomes more complicated than the previous case, as seen in Fig. 4(c-1).

3. Summary

We found from the simulation results that the strong magnetic flux is generated and the charge separation with a quadrupole-like structure is produced during coalescence of magnetic islands in a current sheet. It is found that the electromagnetic waves are emitted in the decay phase of the charge separation and strong Alfvén waves are emitted in the decay phase of

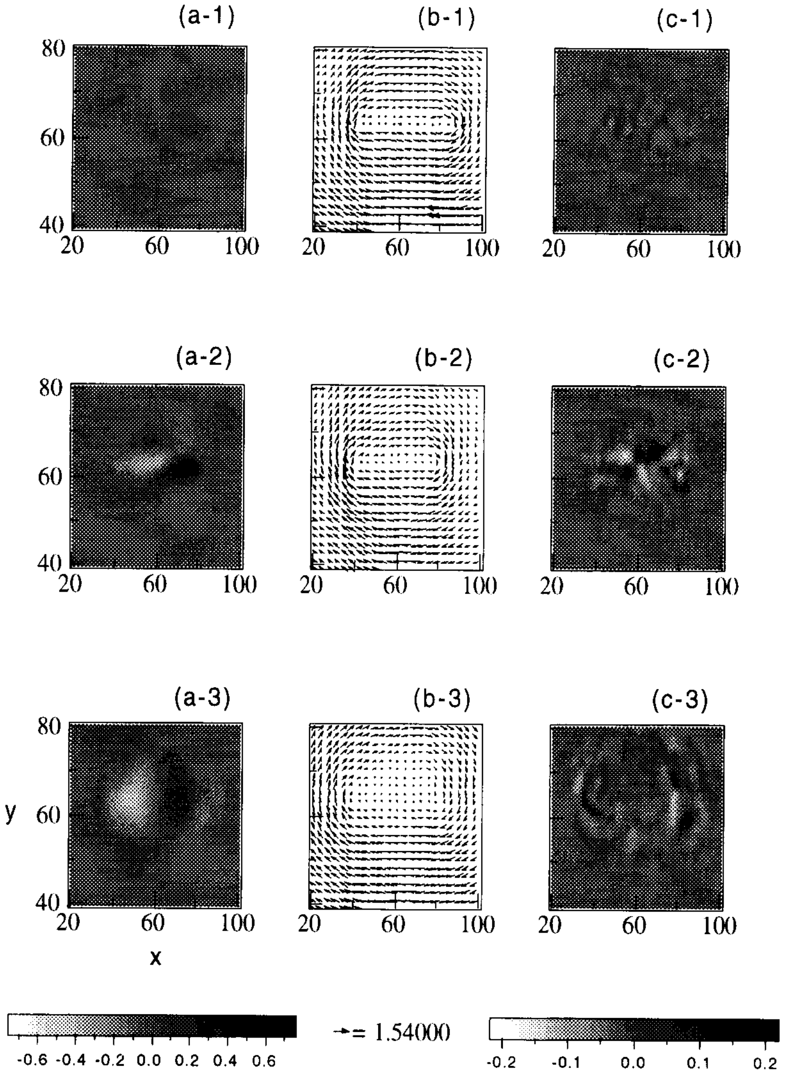

Fig. 2 The time development of the magnetic flux B_z at (a-1) $\omega_{pe}t = 28.46$, (a-2) 31.62 and (a-3) 36.89. The time development of magnetic islands at (b-1) $\omega_{pe}t = 28.46$, (b-2) 31.62 and (b-3) 36.89. The time development of the spatial distribution of the electric charge density $(\rho_+ - \rho_-)$ at (c-1) $\omega_{pe}t = 28.46$, (c-2) 31.62 and (c-3) 36.89.

the strong localized magnetic flux.

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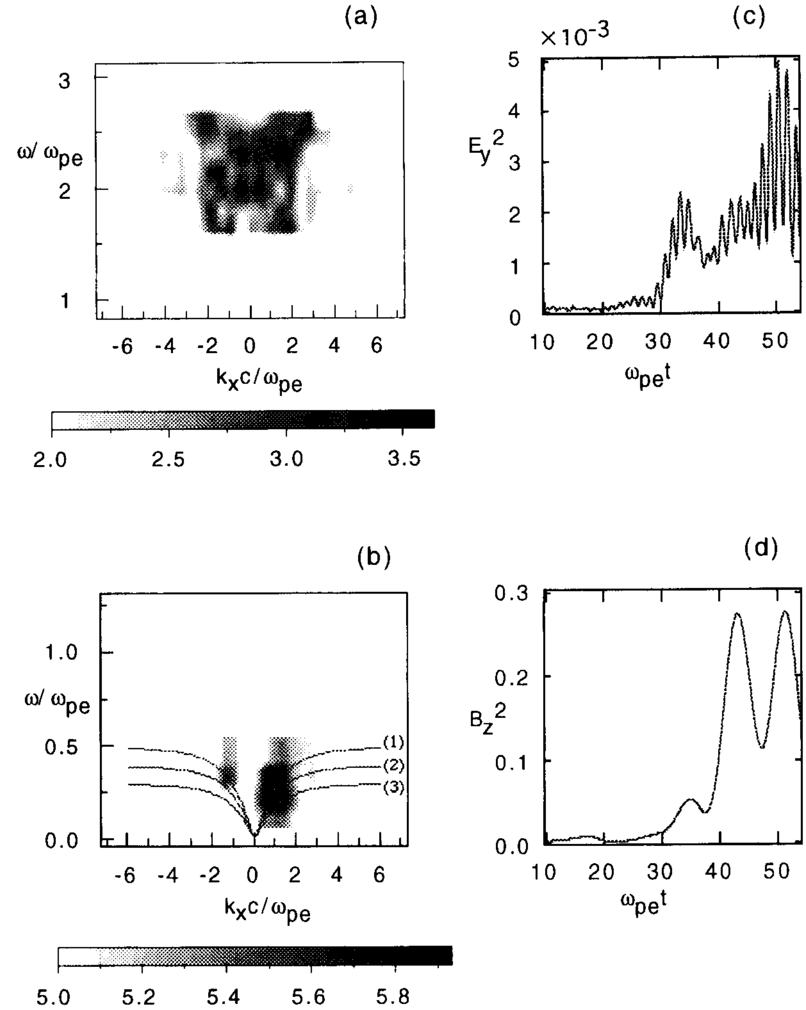

Fig. 3 The dispersion relation of (a) the electromagnetic waves and (c) the Alfvén waves propagating along the magnetic field B_x. The time history of (b) the electric field energy E_y^2 and (d) the magnetic field energy B_z^2.

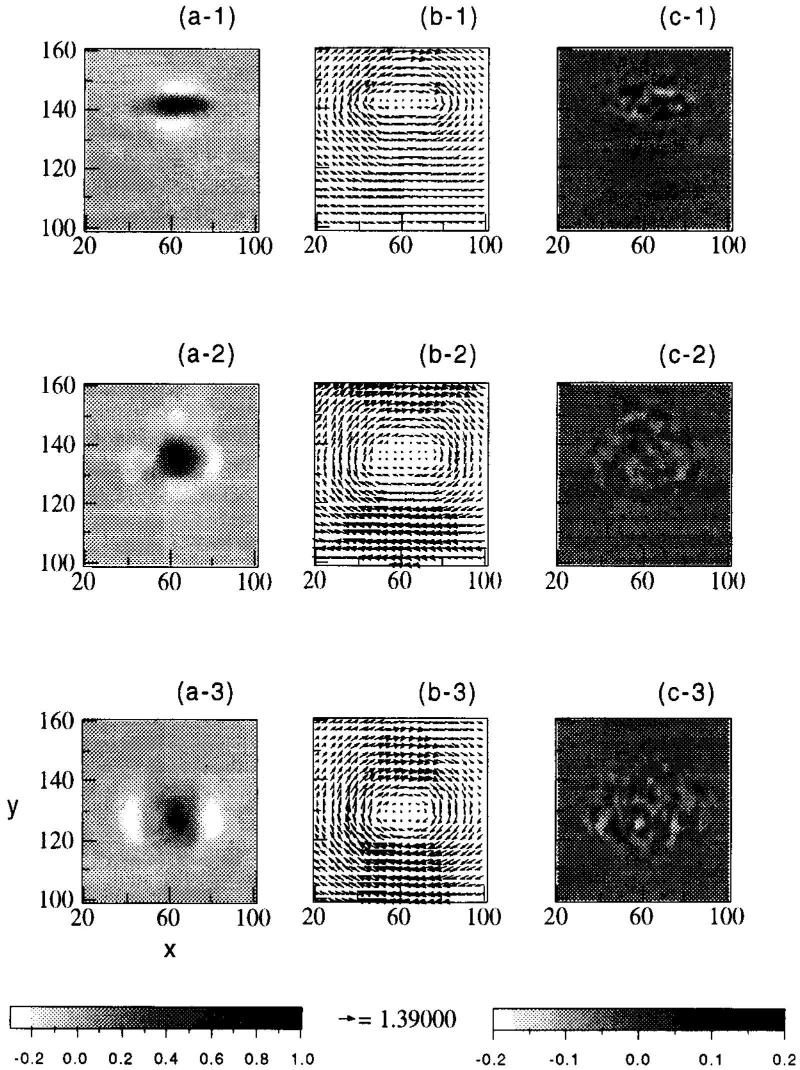

Fig. 4 For a thick current sheet with a width of twice electron skin depth, the time development of the magnetic flux B_z at (a-1) ω_{pe} = 36.89, (a-2) 42.16 and (a-3) 47.43. The time development of magnetic islands at (b-1) $\omega_{pe}t$ = 36.89, (b-2) 42.16 and (b-3) 47.43. The time development of the spacial distribution of the electric charge density ($\rho_+ - \rho_-$) at (c-1) $\omega_{pe}t$ = 36.89, (c-2) 42.16 and (c-3) 47.43.