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Generation of Magnetic Fields near Kelvin-Helmholtz Instability Region in Pair Plasmas

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Abstract

We present the simulation results by using a two-dimensional electromagnetic and relativistic particle-in-cell (PIC) code that quasi-static magnetic field can be generated in the Kelvin-Helmholtz instability region in unmagnetized pair plasmas.

Keywords:

Pair plasma, Kelvin-Helmholtz instability, magnetic field generation

1. Introduction

The Kelvin-Helmholtz instability is a macroscopic instability that grows in a velocity shear layer, causing momentum exchange through vortex motions between two velocity layers.

It was reported recently [1] that the high-frequency electromagnetic waves can be excited from the Kelvin-Helmholtz instability region in pair plasmas. And it was reported [2] that the whistler waves and the high-frequency electromagnetic waves can be excited from the Kelvin-Helmholtz instability and the whistler waves are excited stronger than the electromagnetic waves in magnetized electron-ion plasmas.

Using a two-dimensional electromagetic and relativistic PIC code, we show that quasi-static magnetic fields are generated from a region where the Kelvin-Helmholtz instability develops in pair plasmas from an unmagnetized state ($B_0 = 0$). Then we investigate the energy conversion rate that the initial flow energy is converted to the quasi-static magnetic field energy, by changing the flow velocity.

2. Simulation Model

To set up the situation where the Kelvin-Helmholtz instability occurs in the simulation domain, we impose counter-streaming regions; $v_0 = -0.7c$ in two regions of $0 \le x \le 50$ and $150 \le x \le 200$, and $v_0 = 0.7c$ in the region of $50 \le x \le 150$.

We compare two cases: one is sharp change of the flow veocity on $x = 50$ and $x = 150$, and the other is smooth change of the flow velocity as follow,

$$v_0 = 0.3c\{\tanh(\frac{x-100}{L}) - \tanh(\frac{x-300}{L}) - 1\}$$

where $L = 5$ is about the electron skin depth. In the second case, we use the same parameters as the first case, except for the velocity profile.

3. Simulation Results

In the simulation, the background magnetic field B_0 is zero. But there is a fluctuating magnetic field (seed field) initially owing to the electric current arising from the unbalanced motions of positrons and electrons. Then the magnetic field is amplified from the fluctuating level ($B_z^2 \approx 2.5 \times 10^{-2}$) to form a quasi-static magnetic field.

Figures 1 and 2 show the simulation results for the sharp velocity boundary. Fig. 1 shows the spacial distribution of the magnetic field B_z from $\omega_{pe}t$ = 14.9 to $\omega_{pe}t$ = 74.5. In the initial stage, the quasi-periodic magnetic field structure with a size of the electron skin depth can be generated in the Kelvin-Helmholtz unstable regions, and it grows to a large structure. After $\omega_{pe}t$ = 59.6, four pairs with positive and negative magnetic polarity are generated and the structrure remains to be unchanged.

Figures 2(a) and 2(b) show the time history of the flow kinetic energy in the x and y-direction, respectively. Figure 2(c) shows the time history of the magnetic field energy B_z^2 in the whole system. In the final stage, B_z^2 is almost a constant as shown in Fig. 2(c).

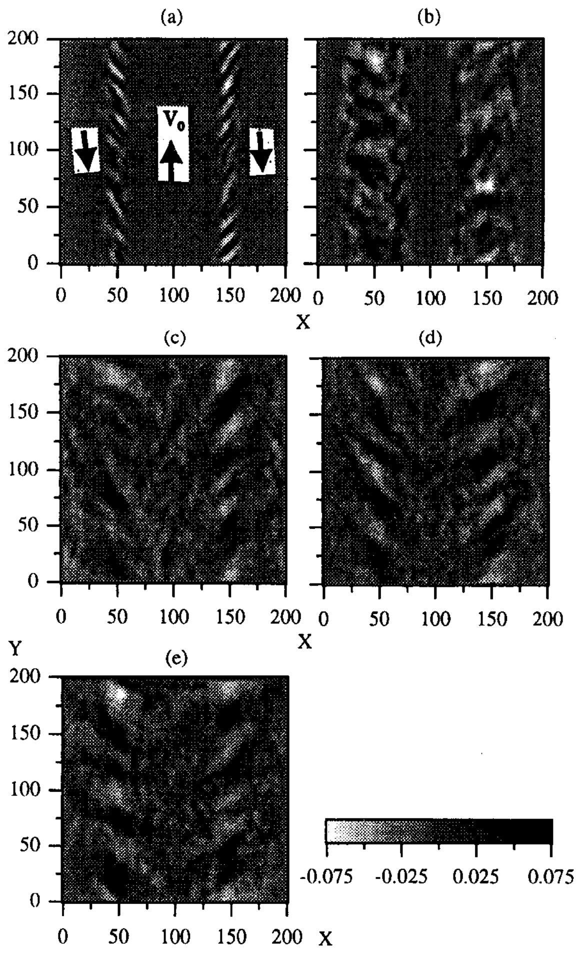

Fig. 1 The time development of the magentic field B_z: (a) $\omega_{pe}t$ = 14.9, (b) 29.8, (c) 44.7, (d) 59.6, (e) 74.5.

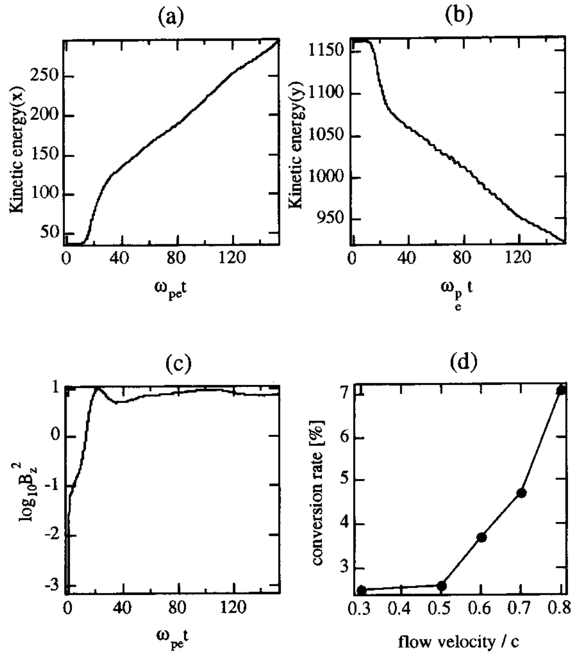

Fig. 2 The time history of the kinetic energy in (a) x-direction, (b) y-direction, and the magnetic field energy (c) B_z^2 and (d) the energy conversion rate.

As the result, about 2.5% of the initial flow energy is converted to the magnetic field energy B_z^2. But in the final stage, all flow energy are shifted the kinetic energy in the y-direction.

We calculate the energy conversion rate that flow energy is converted to the quasi-static magnetic field energy, by changing the flow velocity as shown in Fig. 2(d). As seen this figure, the conversion rate varies rapidly from flow velocity = $0.5c$.

Figures 3 and 4 show the simulation results for the smooth velocity boundary. Figure 3 shows the spacial distribution of the magnetic field B_z from $\omega_{pe}t$ = 14.9 to $\omega_{pe}t$ = 74.5. Compared with Fig. 1, we find that two pairs with positive and negative magnetic polarity are generated after $\omega_{pe}t$ = 59.6.

Figs. 4(a) and 4(b) show the time history of the flow kinetic energy in the x and y-direction, respectively. The kinetic energy in the x-direction is still increasing and the kinetic energy in the y-direction is still decreasing beyond the final stage. Fig. 4(c) shows the time history of the magnetic field energy B_z^2 in the whole system. An increase of the magnetic field energy B_z^2 is noise level until $\omega_{pe}t$ = 25. And the Kelvin-Helmholtz instability grows from about $\omega_{pe}t$ = 25. About 4.1% of the initial flow energy is converted to the

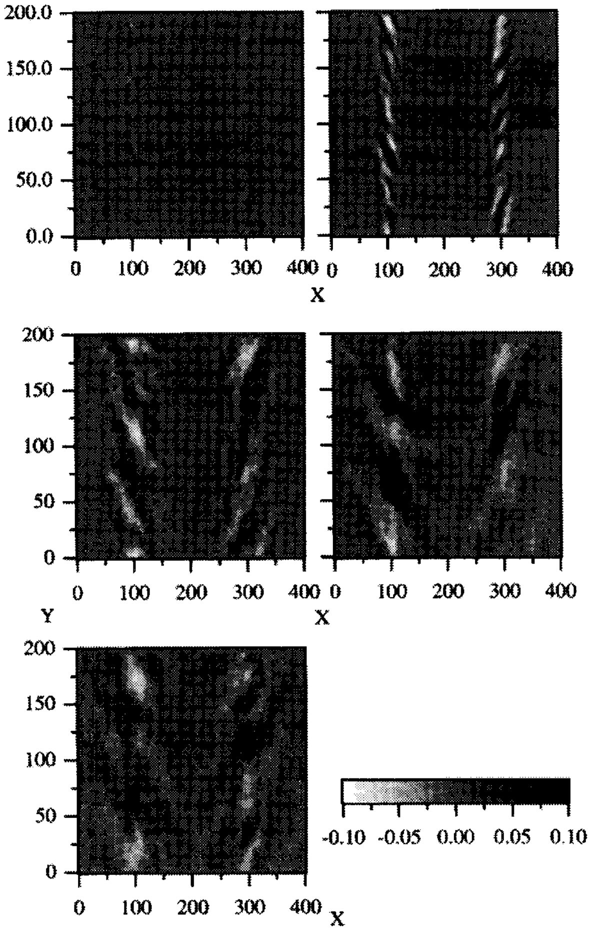

Fig. 3 The time development of the magentic field B_z: (a) $\omega_{pe}t$ = 14.9, (b) 29.8, (c) 44.7, (d) 59.6, (e) 74.5.

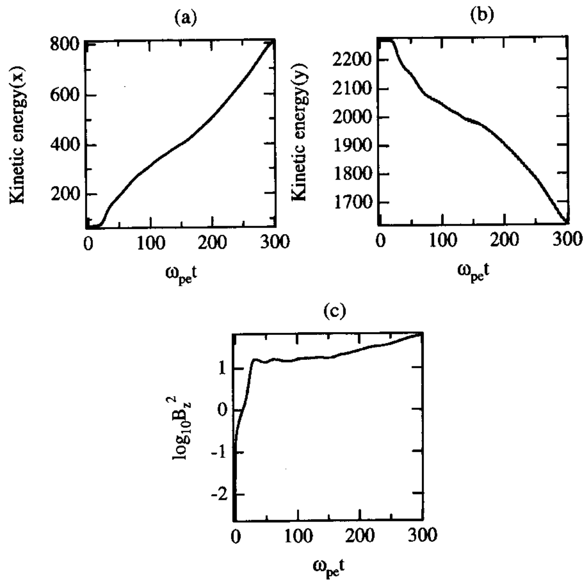

Fig. 4 The time history of the kinetic energy in (a) x-direction, (b) y-direction, and the magnetic field energy (c) B_z^2.

magnetic field energy. The conversion rate of the second case is about 1.6 times effective than the first case.

We compare Fig. 2(c) with Fig. 4(c). In the sharp velocity boundary case (Fig. 2(c)), the Kelvin-Helmholtz instability grows rapidly. That is, the instability is excited strong in the non-linear stage. Then it results in the rebound of the magnetic field energy B_z^2 and then the magnetic field energy decreases a little. The time history of the electric field energy E_y^2 shows the same development with the magnetic field energy. While in the smooth velocity boundary case (Fig. 4(c)), the Kelvin-Helmholtz instability grows slowly. Then it doesn't cause the rebound. Therefore the energy conversion rate of the smooth velocity boudary case is stronger than the sharp velocity boundary case.

4. Conclusion

Using a two-dimensional electromagnetic and relativistic PIC code, we have shown that the quasi-static magnetic fields in the z-direction can be strongly generated from a region where the Kelvin-Helmholtz instbility develops. The conversion rate from the initial flow energy to the magnetic field energy is about a few percent. The process of quasi-static magnetic field generation near the region with the velocity shear would be important for understanding magnetic field generation in astrophysical plasmas.

Acknowlegment

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