Generation of magnetic fields by shear-flow instability in pair plasmas

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We investigate the generation mechanism of magnetic fields by shear-flow instability in pair plasmas, by using a 2-dimensional particle-in-cell code. We also investigate the efficiency of the conversion of the flow energy to the magnetic field energy by changing the external magnetic field intensity. We found that the energy conversion is very efficient with about 20\% for the moderate intensity of the external magnetic field.

Key words: shear-flow instability, magnetic field generation, pair plasmas

1 Introduction

It is well known that the magnetic field plays important roles in the astrophysical plasmas. The generation process and dissipation process of the magnetic fields in the astrophysical plasmas are important subjects and have been investigated for many years. Until now two types of the generation process of the magnetic fields were investigated. The first one is so-called dynamo mechanism to find some amplification processes of the seed magnetic field. The second one is to study the generation processes of the seed magnetic fields.

In many astrophysical plasmas there occur plasma flows driven by many processes that should be non-uniform and result in shear flows. It is well known that the Kelvin-Helmholtz (K-H) instability [1] occurs in the boundary layer by shear flow. The K-H instability is a macroscopic instability that grows in a velocity shear layer, causing momentum exchange through vortex motions between two velocity layers. The K-H instability has been investigated extensively for two main applications in space plasmas and in astrophysical plasmas. Sakai et al. [2] showed that both whistler and electromagnetic waves can be emitted from a region where an electron shear-flow instability occurs in electron-ion plasma. The shear-flow instability is a microscopic instability associated with electron dynamics, contrast to the macroscopic K-H instability.

In this paper we investigate the generation mechanism of magnetic fields by shear-flow instability in pair plasmas, by using a 2-dimensional particle-in-cell code. We also investigate the efficiency of the conversion of the flow energy to the magnetic field energy by changing the external magnetic field intensity. We found that the energy conversion is very efficient with about 20\% for the moderate intensity of the external magnetic field.

2 Simulation model

We use a two-dimensional fully relativistic electromagnetic particle-in-cell (PIC) code, assuming that the physical quantities are constant in z. Our simulation model is drawn in Figure 1. The initial state is characterized by \( E_0 = 0 \) everywhere in the domain. The periodic boundary condition is imposed on particles and field in x-direction, while the free boundary condition is set on particles and fields in y-direction. The skin depth is \( c/\omega_{pe} = 10\Delta \). The simulation step is \( \omega_{pe}\Delta t = 0.05 \). The particle number density is about 100 particles per cell. There are 16 million electron-positron pairs. To set up such
that the shear-flow instability occurs in the simulation domain, we impose following counter-streaming flows as follows:

\[ V_0 = V_d \tanh \left( \frac{y - 200}{L} \right) \]  

(1)

The maximum flow velocity \( V_d = 0.9c \), where \( c \) is light velocity, taken as \( c = 0.5 \). The shear flow width \( 2L \) is taken as \( 2L = 8.0\Delta \). The system size is \( L_x = L_y = 400\Delta \), where \( L_x \) and \( L_y \) are the length of the system in two dimensions and \( \Delta(=1) \) is the grid size.

\[ \text{Figure 1: Simulation model} \]

We investigate three cases: The case (1) where the initial state is characterized by \( B_0 = 0 \) everywhere in the domain. The case (2) where the ratio of plasma frequency \( \omega_{pe} = (e^2n/\epsilon_0m_e)^{1/2} (\epsilon_0 = 1) \) to the electron cyclotron frequency \( \omega_c = eB_0/m_e \), \( \omega_c/\omega_{pe} \) is taken as 0.16, where the Alfvén velocity is \( V_A = 0.08c \). The case (3) where \( \omega_c/\omega_{pe} = 1.6 \), and \( V_A = 0.42c \). For case (2) and case (3), a homogeneous ambient magnetic field is in the x-direction.

3 Simulation results

3.1 The case (1) without magnetic field

Figs. 2(a) and 2(b) present the time development of the magnetic field energy in the z-direction that is normalized by the initial kinetic flow energy and kinetic energy of electron and positron in the system. As seen in Fig.2(a), about 2.5 % of the flow kinetic energy can be converted to the magnetic energy in the final stage of the simulation. The magnetic field energy grows exponentially after about \( \omega_{pe}t = 45 \). The time development of the spacial distribution is shown in Figs. 3(a), (c) and (e) at \( \omega_{pe}t = 45 \). The shear-flow instability grows near interface at \( y = 200 \), where counter-streams exist. In Fig.3(a) the spacial structure of the excited magnetic field \( B_z \) is shown. The reason why the magnetic field \( B_z \) can be generated near the interface of the counter streams is due to the fact that the vortex motions of electrons and positrons in the x-y plane are not completely same, resulting in the formation of the current flows. The different vortex motions of electrons and positrons are seen in Figs. 3(c) and 3(e), respectively.

3.2 The case (2) with weak magnetic field

Figs. 2(c) and 2(d) present the time development of the magnetic field energy in z-direction that is normalized by the initial kinetic flow energy and kinetic energy of electron and positron in the system. As seen in Fig. 2(c), about 20 % of the initial flow energy can be converted to the magnetic energy with very efficient conversion rate. The magnetic field energy grows exponentially after about \( \omega_{pe}t = 55 \).

The time development of the spacial distribution is shown in Figs. 3(b), (d) and (f) at \( \omega_{pe}t = 55 \). The shear-flow instability grows near interface at \( y = 200 \), where counter-streams exist. In Fig.3(b) the spacial structure of the excited magnetic field \( B_z \) is shown. The perturbed region of the instability becomes larger than the previous case and the scale of the vortex motions becomes smaller than the previous case. Furthermore the excited magnetic field intensity becomes stronger than the previous case.
3.3 The case (3) with strong magnetic field

Figs. 2(e) and 2(f) present the time development of the magnetic field energy in z-direction that is normalized by the initial kinetic flow energy and kinetic energy of electron and positron in the system. As seen in Figs. 2(e), about 4% of the flow energy kinetic energy can be converted to the magnetic energy. The shear-flow instability seems to be suppressed in the strong magnetic field case.

![Figure 2: Time history of magnetic field energy](image)

Figure 2: Time history of magnetic field energy: (a) no magnetic field, (c) weak magnetic field and (e) strong magnetic field. The time history of electron flow kinetic energy (1) and positron flow kinetic energy (2) for (b) no magnetic field, (d) weak magnetic field and (f) strong magnetic field.

![Figure 3: Spacial structure of generated magnetic field](image)

Figure 3: The spacial structure of generated magnetic field $B_z$ in the x-y plane and vector plots of electron and positron flows, $V_x$ vs. $V_y$ at (a), (c) and (e) at $\omega_{pe}t = 45$ in the case of no magnetic field and (b), (d) and (f) at $\omega_{pe}t = 55$ in the case of weak magnetic field.
4 Summary

We investigated the generation mechanism of magnetic fields by shear-flow instability in pair plasmas, by using a 2-dimensional particle-in-cell code. We also investigated the efficiency of the conversion of the flow energy to the magnetic field energy by changing the external magnetic field intensity. We found that the energy conversion is very efficient with about 20 % for the moderate intensity of the external magnetic field.

References
