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Particle Acceleration during Counter-Streaming Instability in Magnetized Pair Plasmas

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Abstract

The electromagnetic counter-streaming instability (EM-CSI) in magnetized pair (electron-positron) plasmas with the external magnetic field parallel to the streaming direction is investigated by the particle-in-cell simulation. It is shown that the counter-streaming instability changes its character from magnetic to electrostatic nature when the external magnetic field increases as $\omega_{ce} > 1.5\omega_{pe}$. The electrostatic waves growing due to the electrostatic counter-streaming instability (ES-CSI) play an important role for producing fast electrons and positrons with energy of MeV. The process of high-energy particle production in relativistic shocks in magnetized pair plasmas may be applied to gamma-ray burst events.

Keywords:

Gamma-ray burst event, particle acceleration, magnetized pair plasma

1. Introduction

Gamma-ray bursts (GRBs) [1] are the most powerful events in nature. These events release most of energy as photons with energies in the range from 30 keV to a few MeV. The data are in general agreement with a relativistic shock model, where the prompt and afterglow emissions correspond to synchrotron radiation from shock-accelerated electrons. Therefore, the existence of magnetic fields in the relativistic shock model of the GRBs is essential to explain the emission by the synchrotron radiation [2]. The recent discovery of a strongly polarized GRBs [3] support the presence of strong, ordered magnetic field at the GRBs source. However, since there is only single observation for it, more evidence may be required to demonstrate the existence of ordered magnetic field.

Many authors (e.g., [4], [5], [6]) investigated the counter-streaming instability by using a two or three dimensional PIC code. Only Nishikawa *et al.* [6] investigated the effects of weak external magnetic field to counter-streaming instability. Their result was similar to those without the external magnetic field.

In this paper we investigate numerically, how the counter-streaming instability in un-magnetized pair plasmas is influenced by the external magnetic field parallel to the streaming direction. It is shown from the particle-in-cell (PIC) simulation that the EM-CSI changes its character from magnetic to electrostatic nature when the external magnetic field increases. The electrostatic waves growing due to ES-CSI play an important role for producing fast electrons and positrons with energy of MeV. The process of high-energy particle production in relativistic shocks in magnetized pair plasmas may be applied to GRBs event.

2. Simulation model

We used two-dimensional, fully electromagnetic, and relativistic particle-in-cell code [1]. The lengths of system are $L_x = 4000\Delta$ and $L_y = 64\Delta$, where Δ is grid size. The periodic boundary conditions are imposed in both x and y direction. There are 60 electron-positron pairs in a cell uniformly in whole system. The initial state of the plasma in the left side region ($x \le 2000\Delta$) has the shifted Maxwellian with $v_d = +0.5c$, and in the right side region ($x > 2000\Delta$) has that with $v_d = -0.5c$, where c is light velocity. The external magnetic field is parallel to the counter-streaming direction (x direction). The other parameters are as follows: the simulation time step is $\omega_{pe}\Delta t = 0.05$, where ω_{pe} and Δt are electron plasma frequency and a time step, respectively; the Debye length and skin depth are 1Δ (grid size) and 10Δ, respectively; the both electron and positron thermal velocity are 0.1c. We performed the several simulations by changing the ratio of ω_{ce}/ω_{pe} related to the external magnetic field.

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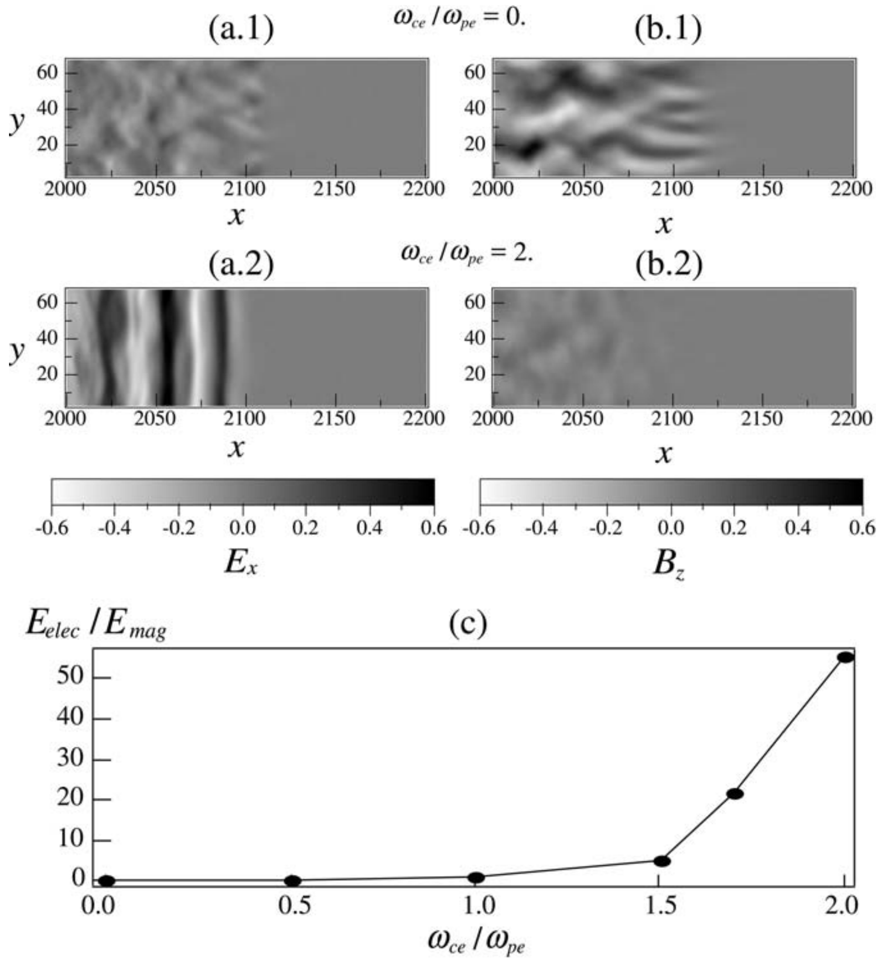

Fig. 1 The spatial distribution of generated electric field E_x (a.1) and generated magnetic field B_z (b.1) at $\omega_{pe}t = 25$, without the external magnetic field. The spatial distribution of generated electric field E_x (a.2) and generated magnetic field B_z (b.2) at $\omega_{pe}t = 25$, when $\omega_{ce}/\omega_{pe} = 2$. (c) shows the ratio between generated electic field energy $E_{elec} = \int\int E_x^2 dxdy$ and magnetic field energy $E_{mag} = \int\int B_z^2 dxdy$ in the simulation domaion at $\omega_{pe}t = 25$.

3. Simulation results

The both electric field and magnetic field are generated by counter-streaming instability. In Figs. 1(a.1) and 1(b.1) show the spatial distribution of generated electric field E_x (parallel component of counter-streaming) and generated magnetic field B_z, respectively, at $\omega_{pe}t = 25$, without the external magnetic field parallel to the streaming direction. Figures. 1(a.2) and 1(b.2) show the spatial distribution of generated electric field E_x and generated magnetic field B_z, respectively, at $\omega_{pe}t = 25$, when $\omega_{ce}/\omega_{pe} = 2$. The generation of magnetic fields due to the electromagnetic counter-streaming instability (EM-CSI) is restrained by the external magnetic field, while the generation of electrostatic fields due to the electrostatic counter-streaming instability (ES-CSI) is enhanced. Figure 1(c) shows the ratio between generated electric field energy $E_{elec} = \int\int E_x^2 dxdy$ and magnetic field energy $E_{mag} = \int\int B_z^2 dxdy$ in the simulation domain at $\omega_{pe}t$ = 25. The external magnetic field intensity is parameterized as ω_{ce}/ω_{pe}. As seen in Fig. 1(c), the electric field energy associated with the ES-CSI exceeds the magnetic field energy rapidly for $\omega_{ce}/\omega_{pe} = 1.5$. The results show that the counter-streaming instability changes its character from magnetic to electrostatic nature when the external magnetic field increases.

The generated electrostatic fields can accelerate the particles parallel to the external magnetic field. Figures. 2(a) and 2(b) show the electron energy distributions without the external magnetic field, and with $\omega_{ce}/\omega_{pe} = 2$, respectively. The horizontal axis shows the electron Lorentz Γ, while the vertical axis shows $\log f_e$. The dotted and solid distributions are the initial and final state ($\omega_{pe}t = 150$), respectively. As seen in Fig. 2(a) and 2(b), the particles are more effectively accelerated by the electrostatic waves under the external magnetic field. The energy spectra of both conditions in their high energy regions is characterized by an exponential-type law. From these simulations we conclude that both electrons and positrons can be accelerated with MeV energy during the counter-streaming instability. For the strong external magnetic field, the particle acceleration in pair plasmas becomes more effective than for the case of un-magnetized pair plasmas.

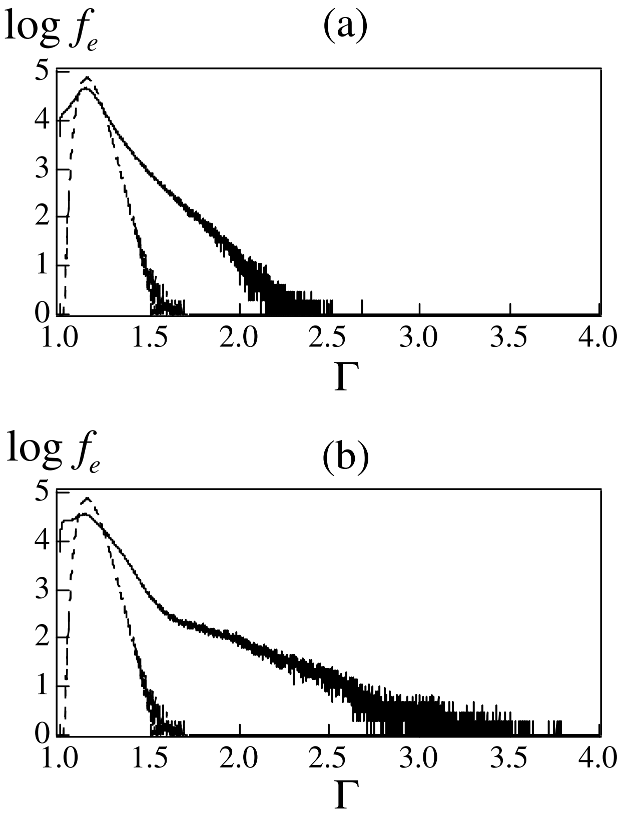

Fig. 2 The electron energy distributions (a) without the external magnetic field, and (b) with ω_{ce}/ω_{pe} = 2. The horizontal axis shows the electron Lorentz Γ, while the vertical axis shows log f_e. The dotted and solid distributions are the initial and final state ($\omega_{pe}t$ = 150), respectively.

4. Summary and discussions

We investigated the electromagnetic counter-streaming instability in magnetized pair plasmas, using a two-dimensional, fully electromagnetic, relativistic particle-in-cell code. It was found that the generated electrostatic waves can accelerate both electrons and positrons up to the energy of a few MeV. We found that the energy spectrum of the accelerated particles is the exponential-type in the high energy region.

The counter-streaming instability in magnetized pair plasmas may be applicable for the GRBs mechanism for both production of collisionless shocks as well as high energy particles of order of a few MeV. However, since there is only single observation that proves the existence of ordered magnetic field at GRBs source, we need the more observational evidence which demonstrates the presence of strong, ordered magnetic field.

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