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Particle acceleration by a large-amplitude wave associated with an ion beam in a magnetized plasma

HIROKI HASEGAWA[1]†,
SEIJI ISHIGURO[1,2] and MASAO OKAMOTO[1,2]

[1]Theory and Computer Simulation Center, National Institute for Fusion Science,
Oroshi-cho 322-6, Toki 509-5292, Japan

[2]The Graduate University for Advanced Studies (Soken-dai), Oroshi-cho 322-6,
Toki 509-5292, Japan

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Abstract. Large-amplitude waves associated with a relativistic ion beam in a magnetized plasma are investigated by means of relativistic electromagnetic particle simulations. In the simulations, it is shown that electromagnetic fields are induced by an ion bunch which has Gaussian density distribution and that their profiles are similar to those of magnetosonic solitons. Further, when an ion beam propagates obliquely to the external magnetic field, it is found that an induced electric field has a parallel component along the magnetic field. Then, as the next step, giving another positron bunch, it is observed that some particles in a positron bunch are accelerated by the parallel electric field.

1. Introduction

Plasma-based accelerators have been extensively studied by many authors. It was found that a wake of plasma oscillations driven by a laser light accelerates electrons [1]. Recently, an ion acceleration by a laser-driven shock wave was reported [2]. Further, an electron acceleration by a wake plasma wave excited by a relativistic electron beam was investigated [3]. A wake field created by a positron beam was also studied [4]. In many studies, however, unmagnetized plasmas are considered.

On the other hand, in magnetized plasmas, several mechanisms of particle acceleration by a large-amplitude wave are known. For instance, from particle simulations, it was found that magnetosonic shock waves accelerate hydrogen ions [5], heavy ions [6], electrons [7], fast ions [8], and positrons [9] to high energy.

Thus, in this paper, we study an interaction between a relativistic ion beam and a background plasma in an external magnetic field by means of one-dimensional (one space coordinate and three velocity components), relativistic, electromagnetic, particle simulations with full particle dynamics. Also, we investigate whether such acceleration phenomena in a magnetosonic shock wave occur in a configuration for an accelerator. It is then found that electromagnetic fields are induced by an ion

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† Present address: Earth Simulator Center, Japan Agency for Marine–Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan.

bunch and that their profiles are similar to those of magnetosonic solitons. When an ion beam propagates obliquely to the external magnetic field, it is shown that an induced electric field has a component along the magnetic field. Further, we find that some particles in another positron bunch are accelerated by the parallel electric field.

2. Electromagnetic fields driven by an ion beam

Initially, an ion beam with Gaussian density distribution and rightward momentum is placed near the left boundary of the simulation box. That is, it propagates through a background plasma from the left-hand side of a system.

The simulation parameters are as follows. The total system length is $L = 8192\Delta_{\mathrm{g}}$, where Δ_{g} is the grid spacing. The ion-to-electron rest mass ratio is $m_{\mathrm{i}}/m_{\mathrm{e}} = 1836$. The number of electrons is $N_{\mathrm{e}} = 921\,600$, and the number of ion beam particles is $N_{\mathrm{b}} = 102\,400$. The speed of light is $c = 20\,\omega_{\mathrm{pe}}\Delta_{\mathrm{g}}$, where ω_{pe} is the electron plasma frequency. The initial Lorentz factor of an ion beam is $\gamma_{\mathrm{b0}} = 1.41$, i.e. it propagates in the positive x direction with the initial velocity $v_{\mathrm{b0}}/c = 0.707$. The width of an ion beam is $\sigma_{\mathrm{b0}} = 100\Delta_{\mathrm{g}}$. Thus, the ratio of the peak beam to the background electron density is $n_{\mathrm{b0}}/n_{\mathrm{e0}} = 3.99$. The magnetic field strength is $|\Omega_{\mathrm{e}}|/\omega_{\mathrm{pe}} = 3.0$, where Ω_{e} is the nonrelativistic electron gyrofrequency. The external magnetic field $\mathbf{B}_0$ is in the (x, z) plane; $\mathbf{B}_0 = B_0\,(\cos 45°, 0, \sin 45°)$. The time step is $\omega_{\mathrm{pe}}\Delta t = 0.002$. Following these parameters, if the external magnetic field strength is $B_0 \sim 3\,\mathrm{T}$, we have $n_{\mathrm{e0}} \sim 10^{13}\,\mathrm{cm}^{-3}$ and $\sigma_{\mathrm{b0}} \sim 1\,\mathrm{cm}$.

We show density and field profiles at $\omega_{\mathrm{pe}}t = 120$ in Fig. 1. The ion beam density n_{b}, the electron density n_{e}, the fields E_y, B_z, ϕ, and F have similar profiles, where ϕ is the electric potential and F is the integral of the parallel electric field $E_{\|}$ along $\mathbf{B}$ [7]. On the other hand, profiles of the fields E_x, E_z, and B_y take the form of $\partial B_z/\partial x$. These structures are similar to those of magnetosonic solitons [10, 11].

Figure 2 shows phase space plots $(x, \Delta\gamma_{\mathrm{b}})$ at the end of the simulation run. Here, $\Delta\gamma_{\mathrm{b}}$ is the difference between the final and initial Lorentz factor of beam particles, $\Delta\gamma_{\mathrm{b}} = \gamma_{\mathrm{b}} - \gamma_{\mathrm{b0}}$. In the third panel of Fig. 1, it is found that E_x has positive values at the head of beam and negative values at the tail. Thus, as shown in Fig. 2, ions in the head of beam are accelerated, while those in the tail are decelerated.

Also, the bottom panel of Fig. 1 indicates that the quantity F has large positive values. This suggests that another particle beam can be accelerated along $\mathbf{B}_0$ as in the positron acceleration by a magnetosonic shock wave [9].

3. Particle acceleration by an induced electric field

Next, we have considered another positron bunch moving with a wave induced by an ion beam. Its initial propagation direction and speed are taken to be nearly parallel to the external magnetic field and very close to c, respectively.

In Fig. 3, we present phase space plots (x, γ_{p}) and a profile of F. Here, the external magnetic field $\mathbf{B}_0$ is taken to be $\mathbf{B}_0 = B_0(\cos 50°, 0, \sin 50°)$, the number of electrons is $N_{\mathrm{e}} = 1\,024\,000$, the number of positron bunch particles is $N_{\mathrm{p}} = 102\,400$, the initial Lorentz factor of a positron bunch is $\gamma_{\mathrm{p0}} = 10$, the width of a positron bunch is $\sigma_{\mathrm{p0}} = 50\Delta_{\mathrm{g}}$, the ratio of the peak bunch to the background electron density is $n_{\mathrm{p0}}/n_{\mathrm{e0}} = 7.97$, and other simulation parameters are the same as those in Sec. 2. This figure indicates that some particles in a test bunch are accelerated up to

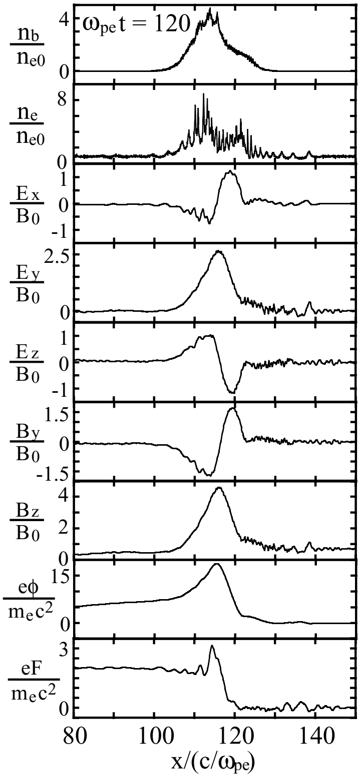

Figure 1. Snapshots of density and field profiles.

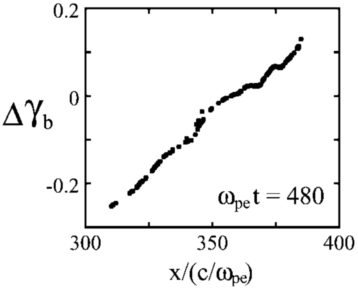

Figure 2. Phase space plots $(x, \Delta\gamma_b)$, where $\Delta\gamma_b$ is the difference from the initial beam Lorentz factor.

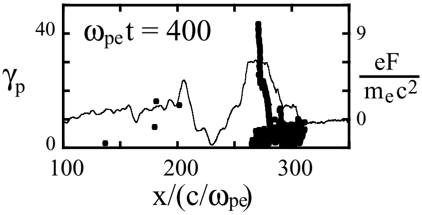

Figure 3. Phase space plots (x, γ_p) and a profile of F.

$\gamma_\mathrm{p} \sim 45$ by the parallel electric field. Then, from orbits of accelerated positrons (which are not shown here), we find that this positron acceleration is thought to occur via the same mechanism as that by a shock wave. On the other hand, since F sometimes becomes negative at the head of induced wave, some positrons are decelerated.

4. Summary

We have numerically studied a large-amplitude wave driven by an ion beam in a magnetized plasma and particle acceleration by this wave. Observed induced waves have electromagnetic fields whose profiles are similar to those of magnetosonic solitons. Further, when an ion beam propagates obliquely to the external magnetic field, an induced electric field has a component along the magnetic field. Then, some particles in another positron bunch are accelerated up to $\gamma_\mathrm{p} \sim 45$ by this parallel electric field with the same mechanism as that by a shock wave.

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