24P161-B

Effect of Magnetic-Field Gradient on Positron Acceleration along the Magnetic Field in an Oblique Shock Wave

斜め衝撃波による陽電子加速に対する外部磁場の非一様性の効果

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The effect of nonuniformity of the external magnetic field $\boldsymbol{B}_0$ on ultrarelativistic positron acceleration along the magnetic field due to shock waves in an electron-positron-ion plasma is studied with use of one-dimensional (one space coordinate and three velocities), fully kinetic, fully electromagnetic, particle simulations with a real mass ratio $m_i/m_e = 1836$. Three cases are examined on shock waves propagating in the positive x direction: 1) uniform $\boldsymbol{B}_0$, 2) $\partial B_{z0}/\partial x > 0$, and 3) $\partial B_{z0}/\partial x < 0$. For the first case, ultrarelativistic acceleration to $\gamma \sim 10^4$ is demonstrated with a simulation with the shock speed $v_{\rm sh}$ close to $c\cos\theta$, where θ is the angle between the external magnetic field and the wave normal. Comparison of the second and third cases shows that a greater number of high-energy positrons are created in the $\partial B_{z0}/\partial x < 0$ case than in the $\partial B_{z0}/\partial x > 0$ case.

1. Introduction

Shock waves propagating obliquely to an external magnetic field $\boldsymbol{B}_0$ in an electron-positron-ion plasma can accelerate positrons to ultrarelativistic energies along the magnetic field [1, 2] with the electric field parallel to the magnetic field $E_\parallel = (\boldsymbol{E}\cdot\boldsymbol{B})/B$ [3, 4], with the time rate of change of the Lorentz factor γ of an accelerated positron

$$\frac{1}{\Omega_p}\frac{d\gamma}{dt} = \frac{c\cos\theta}{v_{\rm sh}}\frac{(\boldsymbol{E}\cdot\boldsymbol{B})}{(\boldsymbol{B}\cdot\boldsymbol{B}_0)}, \tag{1}$$

where Ω_p is the nonrelativistic positron gyrofrequency, c is the speed of light, $v_{\rm sh}$ is the propagation speed of the shock wave, θ is the angle between $\boldsymbol{B}_0$ and the wave normal, $\boldsymbol{E}$ is the electric field, and $\boldsymbol{B}$ is the total magnetic field. In the simulation of Ref. [2], positron energies reached $\gamma \sim 2000$.

The acceleration is particularly enhanced when

$$v_{\rm sh} \sim c\cos\theta, \tag{2}$$

in which relativistic particles can move with the shock wave for long periods of time.

If, however, $\boldsymbol{B}_0$ is not uniform, then not all the region can satisfy the condition (2). This paper investigates the effect of magnetic-field gradient on the positron acceleration, with use of one-dimensional (one space coordinate and three velocities), fully kinetic, fully electromagnetic, particle simulations with the ion-to-electron mass ratio $m_i/m_e = 1836$.

2. Simulation Results

Figure 1 shows positron phase spaces and the profiles of B_z near shock fronts, where shock waves propagate in the positive x direction in an external magnetic field $\boldsymbol{B}_0 = [B_{x0}, 0, B_{z0}(x)]$. Three different cases are compared: 1) uniform $\boldsymbol{B}_0$, 2) $\partial B_{z0}/\partial x > 0$, and 3) $\partial B_{z0}/\partial x < 0$.

In the uniform $\boldsymbol{B}_0$ case depicted in the top panel, the propagation angle is taken to be $\theta = 43°$, and the shock propagation speed is observed to be $v_{\rm sh}/(c\cos\theta) = 1.01$; the condition (2) is therefore met . Positron energies reach $\gamma \sim 10^4$ by the end of the simulation run, $\omega_{pe}t = 7000$. Since the acceleration has not been saturated, γ will continue to rise if we perform a longer simulation run.

The second panel shows the increasing B_{z0} case ($\partial B_{z0}/\partial x > 0$), with the scale length of the gradient $a = 1.5 \times 10^4 c/\omega_{pe}$. The angle θ becomes 43° at the position $x_0 = 3600c/\omega_{pe}$. Although the maximum γ is ~ 8000, only a small fraction of positrons have γ greater than 4000. Since the difference $(v_{\rm sh} - c\cos\theta)$ keeps increasing as the shock wave propagates away from the position x_0, all the positrons eventually move to the downstream region after entering the shock wave.

In the decreasing B_{z0} case (bottom panel), the gradient of B_{z0} is negative; however, the magnitude of a and other parameters are taken to be the same as those in the increasing B_{z0} case. Here, the acceleration is strongest when the shock front is near the point x_0 and has been finished by $\omega_{pe}t = 7000$, with the highest energy close to $\gamma \sim 10^4$. After the encounter with the shock wave, positrons move to the downstream region if $v_{\rm sh} > c\cos\theta$ and go away ahead of the shock front if $v_{\rm sh} < c\cos\theta$. Therefore, positrons that enter the shock wave in the early phase in which $v_{\rm sh} > c\cos\theta$ move to the downstream region, while the positrons encountering the shock wave after $v_{\rm sh}$ has become smaller than $c\cos\theta$ are reflected forward from the shock front to the upstream region. As shown in the bottom panel, therefore, there appears a region where the positron density is quite low.

Although the magnitudes of the field gradient ($|\partial B_{z0}/\partial x|$) are the same for the second and third panels in Fig. 1, the decreasing B_{z0} case creates higher energy positrons than the increasing B_{z0} case. This arises because

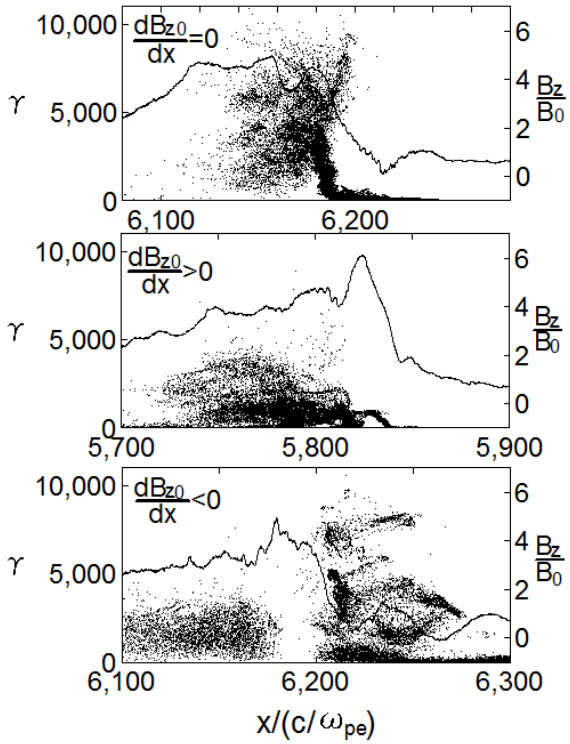

Fig. 1 Snapshots of positron phase spaces (x, γ) near shock fronts. The solid lines show the profiles of B_z. In the top panel with uniform $\boldsymbol{B}_0$, which is plotted at $\omega_{pe}t = 7000$, the highest energy reaches $\gamma \sim 10^4$, and the acceleration has not been saturated till the end of the simulation run. In the second panel with $\partial B_{z0}/\partial x > 0$ plotted at $\omega_{pe}t = 6500$, the number of positrons with $\gamma > 4000$ are quite small. Particles that enter the shock wave eventually move to the downstream region. In the bottom panel with $\partial B_{z0}/\partial x < 0$ at $\omega_{pe}t = 7000$, we find many high energy positrons with $\gamma > 5000$ near the shock front, behind which there is a region of low positron density.

in the former case, positrons that encounter the shock wave when the difference $(v_{\rm sh} - c\cos\theta)$ is about to change from positive to negative values tend to penetrate deep into the shock wave and thus spend long periods of time in the shock transition region before going out to the upstream region.

We plot in Fig. 2 the orbit of a positron in the increasing B_{z0} case in the $(x - v_{\rm sh}t, y)$ plane. The vertical dashed line represents the position at which B_z takes its maximum value. After entering the shock transition region, this positron stays there for $\omega_{pe}t \simeq 2200$ and then moves to the downstream region.

The orbit of a positron in the decreasing B_{z0} case is depicted in Fig. 3. This particle penetrates deep into the shock transition region and stays in the shock wave for a period $\omega_{pe}t \simeq 4000$, after which it is reflected forward to the upstream region.

3. Summary

With use of one-dimensional, fully kinetic, fully electromagnetic particle simulations, we have studied positron

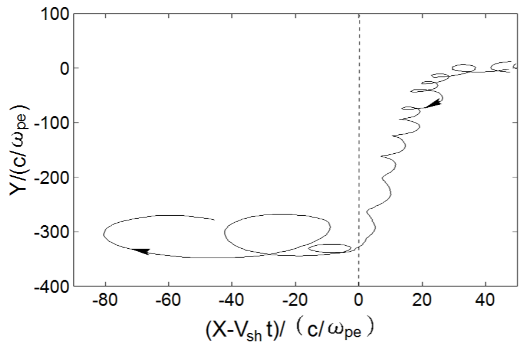

Fig. 2 Orbit in the $(x - v_{\rm sh}t, y)$ plane of a positron in the increasing B_{z0} case. The vertical dashed line indicates the peak position of B_z. This particle stays in the shock transition region for $\omega_{pe}t \simeq 2200$, after which it goes out to the downstream region.

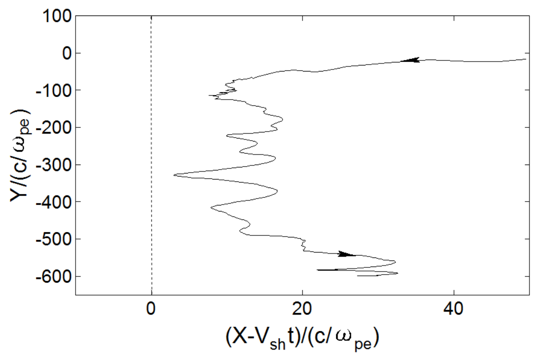

Fig. 3 Orbit in the $(x - v_{\rm sh}t, y)$ plane of a positron in the decreasing B_{z0} case. After entering the shock transition region and staying there for rather a long period of time, this particle goes back to the upstream region.

acceleration along the magnetic field caused by shock waves in an electron-positron-ion plasma, with particular attention to the effect of the nonuniformity of the external magnetic field.

First, we have demonstrated positron acceleration to $\gamma \sim 10^4$ in a uniform $\boldsymbol{B}_0$. Since the acceleration has not been saturated by the end of the simulation run, positron energies would continue to rise in a longer simulation. We have then compared the cases with increasing and decreasing external magnetic fields and found that the positron acceleration is more enhanced in the latter than in the former.

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[4] S. Takahashi, M. Sato, and Y. Ohsawa, Phys. Plasmas **15**, 082309 (8) (2008) 13 pages.