J. Plasma Physics (2006), vol. 72, part 6, pp. 919–923. © 2006 Cambridge University Press
doi:10.1017/S0022377806005307 Printed in the United Kingdom

Simulation studies of positron acceleration by a shock wave

YUKIHARU OHSAWA,[1] K. KATO[1]
and H. HASEGAWA[2]
[1]Department of Physics, Nagoya University, Nagoya 464-8602, Japan
[2]National Institute for Fusion Science, Toki 509-5292, Japan

(Received 8 August 2005 and 29 November 2005)

Abstract. Using a relativistic electromagnetic particle code, we investigate positron acceleration in a shock wave propagating obliquely to an external magnetic field $\mathbf{B}_0$ in an electron–positron–ion plasma. After an encounter with a shock wave, some positrons are reflected and then accelerated along the magnetic field. They stay in the shock transition region and have velocities nearly parallel to $\mathbf{B}_0$. Owing to the deformation of the wave profile, the acceleration can become stagnant. However, if the shock speed v_{sh} is close to $c\cos\theta$, where c is the speed of light and θ is the angle between the wave normal and $\mathbf{B}_0$, the acceleration can start again. In this second stage acceleration, three types of motion are found. The first type is the same as that in the first stage. In the second type, particles gain energy from the electric field perpendicular to the magnetic field in association with large-radius gyromotion. The third type of motion resembles the curtate cycloid in the wave frame. We give theoretical estimates for the energy increase in these processes.

1. Introduction

Non-stochastic particle acceleration mechanisms in shock waves have been extensively studied with theory and particle simulations; see, for instance, [1]. Quite recently, motivated by the studies of pulsars, positron acceleration has also been investigated in [2]. Its one-dimensional (one space coordinate and three velocities), relativistic, electromagnetic particle simulations have shown that an oblique shock wave in a plasma consisting of electrons, positrons, and ions can accelerate some positrons to energies $\gamma \sim 600$, where γ is the Lorentz factor [2]. Positrons are reflected along the magnetic field by the wave electric field. They then move nearly parallel to the external magnetic field $\mathbf{B}_0$. They can stay in the shock transition region for long periods of time if $v_{\mathrm{sh}} \sim c\cos\theta$, where v_{sh} is the shock speed, c is the speed of light, and θ is the angle between $\mathbf{B}_0$ and the wave normal. The increase rate of γ is given by

$$\frac{d\gamma}{dt} = \Omega_{\mathrm{p}} \frac{c\cos\theta}{v_{\mathrm{sh}}} \frac{(\mathbf{E}\cdot\mathbf{B})}{(\mathbf{B}\cdot\mathbf{B}_0)}, \tag{1.1}$$

where Ω_{p} is the non-relativistic positron gyrofrequency [2]. The simulations were performed until $\omega_{\mathrm{pe}}t \sim 2000$, where ω_{pe} is the electron plasma frequency, and the energy increase seemed to almost stop at the end of the simulation runs.

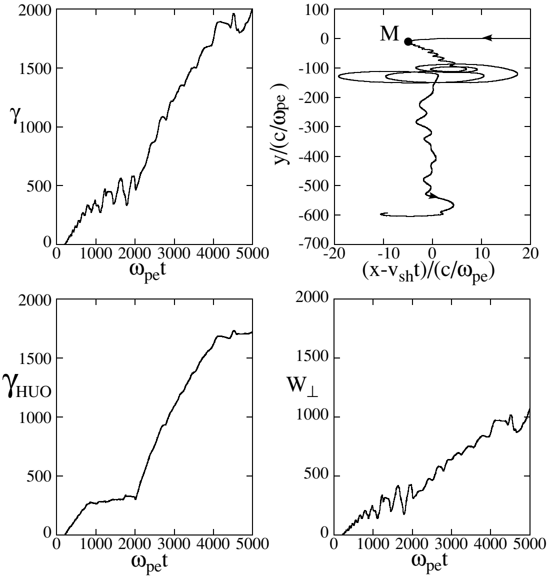

Figure 1. Time variation of γ and orbit in the $(x - v_{\rm sh}t, y)$ plane of an accelerated positron. In the lower panels, time variations of $\gamma_{\rm HUO}$ and $W_\perp$ are also depicted.

In the present paper, we make the system length of the simulation twice as long as previously [2] and observe the long-time behavior of shock waves and accelerated positrons. It is then found that after the plateau of the energy increase, the acceleration is restored. Furthermore, we find three different types of particle motion in this second stage acceleration. By the end of the simulation run, $\omega_{\rm pe}t = 5000$, some positrons are accelerated to $\gamma \sim 2000$.

2. Three types of acceleration

We show simulation results of a shock wave propagating in the x direction with a propagation speed $v_{\rm sh} = 2.43 v_{\rm A}$ in an external magnetic field $\mathbf{B}_0 = B_0(\cos\theta, 0 \sin\theta)$ with $\theta = 42^\circ$. The system length is $L = 16\,384\Delta_{\rm g}$, with $\Delta_{\rm g}$ the grid spacing. The total number of electrons is $N_{\rm e} \approx 1.23 \times 10^6$. The positron-to-electron density ratio is $n_{\rm p0}/n_{\rm e0} = 0.02$. The mass ratio is $m_{\rm i}/m_{\rm e} = 100$. The speed of light is $c/(\omega_{\rm pe}\Delta_{\rm g}) = 4$. The electron gyrofrequency is $|\Omega_{\rm e}|/\omega_{\rm pe} = 3.0$ in the upstream region; thus, the Alfvén speed is $v_{\rm A}/(\omega_{\rm pe}\Delta_{\rm g}) = 1.2$. Other simulation parameters are the same as those in [2].

The upper left panel of Fig. 1 shows the time variation of γ of an accelerated positron. After the encounter with the shock wave at $\omega_{\rm pe}t \approx 200$, the energy γ grows with time. The particle moves nearly parallel to $\mathbf{B}_0$ in the shock transition region. The energy increase then becomes stagnant for $1000 \lesssim \omega_{\rm pe}t \lesssim 2000$. The processes up to this time are essentially the same as those described in [2]. After the plateau, however, the energization begins again and continues until the end of the simulation. The final value of γ is approximately 2000.

The upper right panel shows the orbit in the $(x - v_{\rm sh}t, y)$ plane of this particle. It encounters the shock wave at point M and then moves in the negative y direction

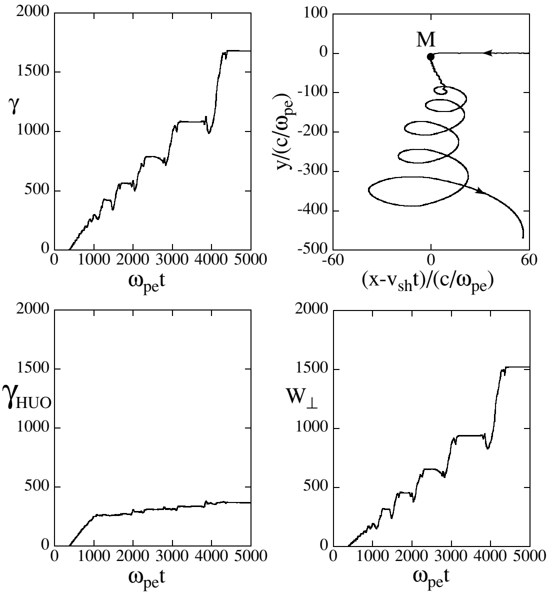

Figure 2. The same four quantities as in Fig. 1 for a positron accelerated by $\mathbf{E}_\perp$.

along the shock front. During the plateau, the particle enters into a turbulent orbit. After the plateau, it again moves in the negative y direction along the shock front.

The lower left panel shows the time variation of $\gamma_{\rm HUO}$, where $\gamma_{\rm HUO}$ is the integral of (1.1) along the particle orbit. Outside the plateau period, the shapes of γ and $\gamma_{\rm HUO}$ are quite similar, indicating that the acceleration processes in the first and second stages are the same. Indeed, both of them are quantitatively accounted for by the theory developed in [2].

The lower right panel of Fig. 1 shows the time variation of $W_\perp$, where $W_\perp$ is the work done by the electric field perpendicular to the magnetic field,

$$W_\perp = \frac{e}{m_{\rm e}c^2}\int \mathbf{E}_\perp \cdot \mathbf{v}\,dt. \tag{2.1}$$

Here $W_\perp$ is normalized to $m_{\rm e}c^2$. In this type of acceleration, the contribution of perpendicular electric field is small; the increase in $W_\perp$ from time $\omega_{\rm pe}t = 2000$ to 4000 is 35% of that in γ.

Figure 2 displays γ, $(x - v_{\rm sh}t, y)$, $\gamma_{\rm HUO}$, and $W_\perp$ of a positron accelerated by the perpendicular electric field. The upper panels show that γ increases stepwise in the second stage acceleration and that the particle performs a large-radius gyromotion. The lower panels show that $\gamma_{\rm HUO}$ is quite small, while $W_\perp$ resembles γ. We thus see that the particle absorbs energy from $\mathbf{E}_\perp$ in association with the gyromotion for $\omega_{\rm pe}t \gtrsim 1000$.

We can understand this acceleration mechanism by applying the theory of incessant acceleration of energetic particles [3], which was originally developed for energetic ions having speeds higher than the shock speed. Gyrating energetic particles that move back and forth between the shock and upstream regions can gain energy from the transverse electric field in the shock region. The particle experiences a jump in γ in each gyroperiod.

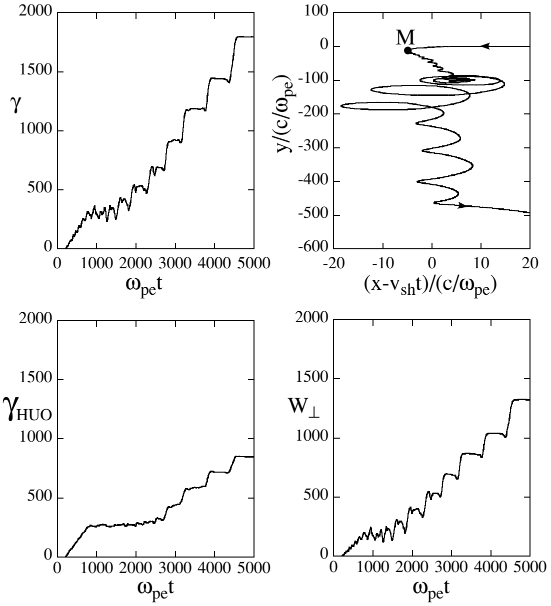

Figure 3. The same four quantities for a positron with a cycloid-like orbit.

Figure 3 shows the same four quantities of another positron. Even though γ rises stepwise in the second stage acceleration, the particle orbit is similar to a curtate cycloid. The lower panels indicate that both parallel and perpendicular electric fields contribute to the energy multiplication. The energy jump takes place at the time of reflection across the magnetic field. The jump in γ is estimated as

$$\delta\gamma = -\frac{v_{\rm sh}}{c^2}\frac{B_{z0}}{B_0}\Omega_{\rm p} v_{y0}(t_{\max}-t_{\min}) + \frac{v_{\rm sh}[p_x(t_{\max})-p_x(t_{\min})]}{m_{\rm p}c^2}, \qquad (2.2)$$

where $t_{\min}$ and $t_{\max}$ are the times of the minima and maxima immediately before and after the reflection, respectively, and v_{y0} is the average velocity in the y direction; its specific form is given in [4, (20)].

The plateau of γ for $1000 \lesssim \omega_{\rm pe}t \lesssim 2000$ is due to the deformation of the field profiles, which arises from the non-stationarity of the shock wave. The field profiles are rather diffusive for that time period, and the particle acceleration almost stops.

3. Summary

We have studied positron acceleration in an oblique shock wave in an electron–positron–ion plasma with relativistic electromagnetic particle simulations. After an encounter with a shock wave, some positrons can be accelerated along the magnetic field. The energy increase, however, can become a plateau owing to the non-stationary wave evolution. However, after the recovery of the field profiles, particle acceleration can start again. In this second stage, three different types of acceleration are found. In the first type, particles move nearly parallel to the magnetic field. This is the same process as that before the plateau [2]. In the second type, particles perform large-radius gyromotions and absorb energy from the transverse electric fields; γ increases stepwise. This mechanism can be understood with the theory of incessant acceleration of energetic particles [3], which was originally developed for ions. The orbits of the third type resemble curtate cycloids. They mainly gain energy upon reflection. A theoretical estimate for the energy increase of this type has been given.

References

[1] Ohsawa, Y. 2004 Nonstochastic particle acceleration in collisionless shock waves. *Physica Scripta* **T107**, 32–35.

[2] Hasegawa, H., Usami, S. and Ohsawa, Y. 2003 Positron acceleration to ultrarelativistic energies by a shock wave in a magnetized electron–positron–ion plasma. *Phys. Plasmas* **10**, 3455–3458.

[3] Usami, U. and Ohsawa, Y. 2002 Long-time behavior of relativistic ions incessantly accelerated by an oblique shock wave. *Phys. Plasmas* **9**, 1069–1072.

[4] Usami, U. and Ohsawa, Y. 2004 Motions of ultrarelativistic particles accelerated in an oblique plasma wave. *Phys. Plasmas* **11**, 3203–3211.