§50. Positron Acceleration by an Oblique Magnetosonic Shock Wave in an Electron-Positron-Ion Plasma

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Electron-positron plasmas can be produced with ultra intense lasers. Also, they are thought to exist in pulsar nebulae or astrophysical jets. In most cases, however, these plasmas will contain ions as well as electrons and positrons. Thus, we have studied magnetohydrodynamic waves [1] and positron acceleration [2-4] in an electron-positron-ion plasma.

We considered a shock wave propagating in the x direction in an external magnetic field $\boldsymbol{B}_0 = B_0(\cos\theta, 0, \sin\theta)$. We have then found that a shock wave can reflect some positrons with the electric field parallel to the magnetic field. If the shock propagation speed $v_{\rm sh}$ satisfies the relation $v_{\rm sh} \sim c\cos\theta$, these reflected particles stay in the shock transition region for long periods of time and gain ultrarelativistic energies.

To analyze this new acceleration mechanism, we assume that the velocities of accelerated positrons satisfy the relations $\gamma \gg 1$ (γ is the Lorentz factor) and $v_x \approx v_{\rm sh} \gg v_y$ and that $v\mathrm{d}\gamma/\mathrm{d}t \gg \gamma|\mathrm{d}\boldsymbol{v}/\mathrm{d}t|$. Hence, in the relativistic equation of motion, we neglect $\gamma \mathrm{d}v_\sigma/\mathrm{d}t$ compared with $v_\sigma \mathrm{d}\gamma/\mathrm{d}t$ where $\sigma = x$, y, or z. Using the relations $E_y = (v_{\rm sh}/c)(B_z - B_{z0})$ and $E_z = -(v_{\rm sh}/c)B_y$, which are obtained from Maxwell equations for a stationary wave, we have the lowest order equations as

$$m_p v_{\rm sh}\frac{\mathrm{d}\gamma}{\mathrm{d}t} = eE_x + e\frac{v_y}{c}B_z - e\frac{v_z}{c}B_y, \quad (1)$$

$$0 = e\frac{v_z}{c}B_{x0} - e\frac{v_{\rm sh}}{c}B_{z0}, \quad (2)$$

$$m_p v_z\frac{\mathrm{d}\gamma}{\mathrm{d}t} = -e\frac{v_y}{c}B_{x0}. \quad (3)$$

From eqs. (1)-(3), we find that these positrons move almost parallel to $\boldsymbol{B}_0$,

$$v_z/v_{\rm sh} = B_{z0}/B_{x0}. \quad (4)$$

Also, we obtain the energy increase rate as

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{eB_{x0}}{m_e v_{\rm sh}}\frac{(\boldsymbol{E}\cdot\boldsymbol{B})}{(\boldsymbol{B}\cdot\boldsymbol{B}_0)}. \quad (5)$$

The particle energy increases almost linearly with time.

Next, we show positron acceleration obtained by a one-dimensional (one space coordinate and three velocity components), relativistic, electromagnetic, particle simulation code with full particle dynamics.

Figure 1 displays time variations of γ and $\boldsymbol{v}$ of a positron accelerated by a shock wave to $\gamma \sim 700$. Its γ linearly increased with time from $\omega_{\rm pe}t \simeq 250$ to $\omega_{\rm pe}t \simeq 1600$. The energy increase rate is $\mathrm{d}\gamma/\mathrm{d}(\omega_{\rm pe}t) = 0.41$, which is in good agreement with a theoretical estimate. The figures of v_x and v_z indicate that the particle moves nearly parallel to the external magnetic field.

Figure 2 shows the trajectory of this positron in the $(x - v_{\rm sh}t, y)$ plane. After the reflection, this particle moves in the negative y direction along the shock front.

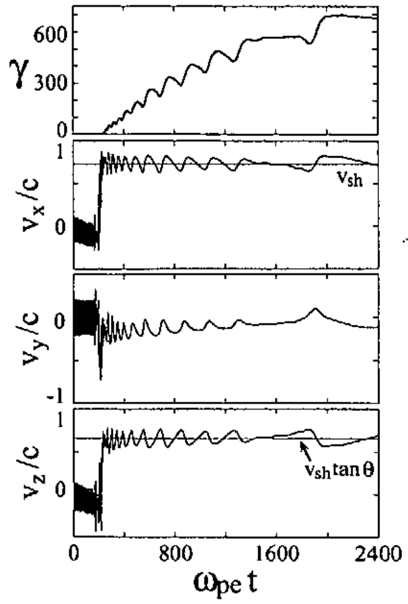

Fig. 1. Time variations of γ, v_x, v_y, and v_z of an accelerated positron.

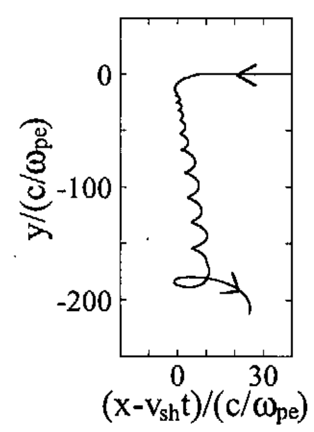

Fig. 2. Orbit of an accelerated positron in the $(x - v_{\rm sh}t, y)$ plane.

References

1) Hasegawa, H. and Ohsawa, Y.: J. Phys. Soc. Jpn. **73** (2004) 1764.

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4) Hasegawa, H. and Ohsawa, Y.: Submitted to Phys. Plasmas.