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Detrapping of Energetic Electrons from an Oblique Shock Wave and its Dependence on External Magnetic Field
斜め衝撃波からの捕捉電子の解放と外部磁場に対する依存性

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With use of two-dimensional, relativistic, electromagnetic, particle simulations, the evolution of a large number of electrons in an oblique shock wave is studied with attention to multi-dimensional effects. Further, the motions of the same number of test electrons are calcurated; the field data averaged along the direction of the shock front, which are obtained from the two-dimensional simulation, are used in the equation of motion. Comparison of the two groups of electons verifies that multi-dimensional effects can cause detrapping of electrons from the main pulse region and subsequent acceleration by the shock wave. It is also confirmed that the detrapping of electrons starts after two-dimensional fluctuations grow to large-amplitudes.

1. Introduction

Particle simulations have revealed [1] that prompt electron acceleration to ultrarelativistic energies can occur in a magnetosonic shock wave propagating obliquely to an external magnetic field with $|\Omega_e|/\omega_{\rm pe}\gtrsim 1$, where Ω_e and $\omega_{\rm pe}$ are the electron gyro and plasma frequencies, respectively. In such a wave, some electrons are reflected near the end of the main pulse of the shock wave, get trapped and are energized in the main pulse. The acceleration is extremely enhanced when the propagation speed of the shock wave $v_{\rm sh}$ is close to $c\cos\theta$, where c is the speed of light and θ is the propagation angle of the shock wave. Once electrons are traapped, they cannot readily escape from the wave [2].

In the above studies, the simulations were one-dimensional (1D). Recently, two-dimensional (2D) particle simulations have shown [4] that after trapping and energization in the main pulse, some electrons can be detrapped from it and can suffer subsequent acceleration by the mechanism studied in Refs. [3]. The detrapping can be caused by magnetic fluctuations along the shock front. In this study, we examine in detail the multi-dimensional effects. In addistion to a two-dimensional particle simulation, we calculate test particle orbits in the 1D filed averaged along the direction of the shock front; the field data are obtained from the 2D particle simulation.

2. Physical Picture of Electron Detrapping

We here present a physical picture of detrapping. The shock wave is assumed to propagate in the x direction with a speed $v_{\rm sh}$ in the external magnetic field in the (x,z) plane, $\boldsymbol{B} = B_0(\cos\theta, 0, \sin\theta)$. In the frame moving with the speed $v_{\rm sh}$ in the x direction, electric and magnetic fields may be written as

$$E_j(\boldsymbol{x},t) = E_{j\rm sh}(x) + \delta E_{j1}(x,t) + \delta E_{j2}(x,y,z,t), \quad (1)$$

$$B_j(\boldsymbol{x},t) = B_{j\rm sh}(x) + \delta B_{j1}(x,t) + \delta B_{j2}(x,y,z,t), \quad (2)$$

where the subscript j refers to x, y, or z, $E_{j\rm sh}$ and $B_{j\rm sh}$ are the time-averaged values of 1D fields, and we assume that $E_{y\rm sh} = E_{y0} = -v_{\rm sh}B_{z0}/c$, $E_{z\rm sh} = 0$, which are equal to the values in the case of the 1D stationary shock wave.

Using the drift approximation, we can write the velocity of the electron as

$$\boldsymbol{v} = v_{\parallel}\boldsymbol{B}/B + c(\boldsymbol{E}\times\boldsymbol{B})/B^2. \quad (3)$$

Substituting Eqs. (1) and (2) into Eq. (3) and neglecting the second order temrs of the fluctuations, we obtain

$$v_x \simeq (c\cos\theta - v_{\rm sh} + \delta v_{x1} + \delta v_{x2})B_o/B_{\rm sh}, \quad (4)$$

$$\delta v_{xl} \simeq \frac{c}{B_0}(\delta E_{yl} + \delta B_{xl}) - \frac{(c\cos\theta - v_{\rm sh})}{B_{z\rm sh}}\delta B_{zl} \quad (5)$$

where l =1 or 2. This indicates that some electrons can be detrapped from the main pulse when they feel the big change in δv_{xl}.

3. Simulation

We carry out 2D (two space coordinates and three velocities), relativistic, electromagnetic particle simulatios with full ion and electron dynamics. The total number of the simulation particles is $N \simeq 1.1\times 10^9$. We follow the motions of 2.1×10^6 electrons in the 2D simulation and call the electrons the 2Ds ones. We also compute the test particle orbits, integrating the relativistic equation of motion

$$\frac{d\boldsymbol{P}}{dt} = e\bar{\boldsymbol{E}}(x,t) + \frac{e}{c}\boldsymbol{v}\times\bar{\boldsymbol{B}}(x,t), \quad (6)$$

where $\bar{\boldsymbol{E}}(x,t)$ and $\bar{\boldsymbol{B}}(x,t)$ are y-averaged data of the field data $\boldsymbol{E}(x,y,t)$ and $\boldsymbol{B}(x,y,t)$ obtained in the 2D simulation. We call the test particles follwing Eq. (6) the 1Dt electrons. The numbers of the 1Dt electrons is the same as that of the 2Ds electrons. The initial positions and velocities of the 1Dt electrons are exactly the same as those of the 2Ds electrons.

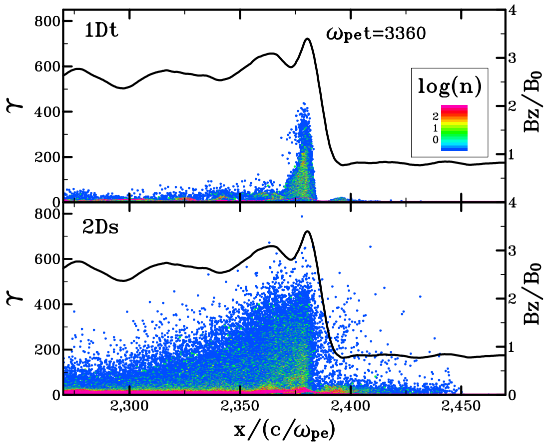

Fig. 1 Phase space plots (x, γ) of the 1Dt and 2Ds electrons and magnetic field profile at $\omega_{pe}t = 3360$.

Figure 1 shows the profile of B_z averaged over the y direction in a shock wave with $v_{sh} \simeq 0.95c\cos\theta$ and the electron number density in the (x, γ) plane at $\omega_{pe}t = 3360$, where γ is the Lorentz factor. In the upper panel, some of the 1Dt electrons are trapped and energized in the main pulse region, and there are no energetic electrons outside the region. However, in the lower panel, many energetic 2Ds electrons exist in the wider region from the upstream to downstream regions. The maximum energy of the 2Ds electrons is higher than that of the 1Dt electrons.

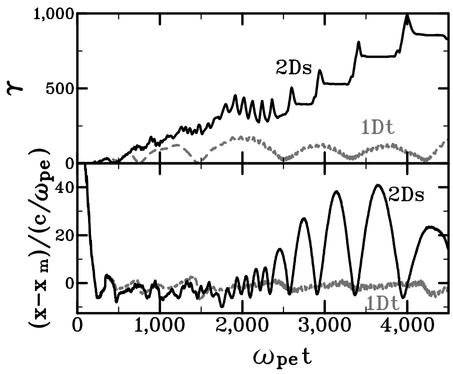

Fig. 2 Time variations in x and γ of 1Dt and 2Ds electrons with the same initial velocities and positions

Figure 2 shows the time variations of γ and the position x of a 2Ds (black solid line) and a 1Dt (gray dashed line) electrons. The initial velocities and positions of the two electrons are exactly the same, and both of them are reflected near the end of the main pulse. However, their orbits after the reflection are completely different. The 1Dt electron continues to be trapped in the main pulse, while the 2Ds electron has been detrapped from it to the upstream region. The 2Ds electron then crosses the shock front several times due to the gyromotion and is further accelerated by the the transverse electric field E_y in the shock wave.

Figure 3 shows the numbers of electrons that have got trapped in the main pulse by the time t (upper panel) and that have been detrapped from it (lower panel). The detrapping of the 2Ds electrons starts at $\omega_{pe}t \simeq 1000$. Figure 4 displays time variations of the magnitudes of δv_{x1} and δv_{x2} defined by Eq. (5). The values of $|\delta v_{x2}|$ are much greater than those of $|\delta v_{x1}|$, which caused the difference between the motions of 1Dt and 2Ds electrons. As predicted by Eq. (5), the 2Ds electrons begins to be detrapped after the increase of $|\delta v_{x2}|$.

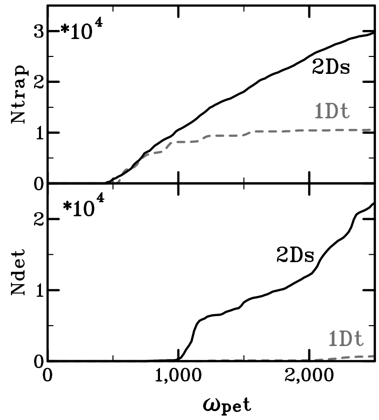

Fig. 3 Time variations in the numbers of trapped and detrapped electrons

4. Summary and Discussion

We have studied electron motion in an oblique shock wave using the 2D particle simulations. Further, we have calcurated test particle motion in the 1D field averaged along the direction of the shock front. Comparison of the simulation and test electrons confirmed that multi-dimensional effects can cause detrapping from the main pulse and subsequent acceleration by the shock wave. In the presentation, we will discuss the dependence on external magnetic field, multi-dimensional effects on reflection, and the evolution of two-dimensional flucutuations.

References

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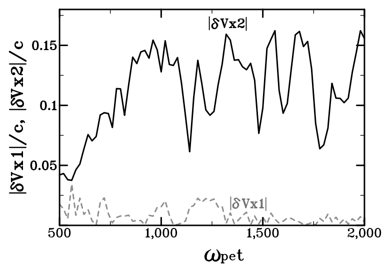

Fig. 4 Time variations in the magnitudes of fluctuations δv_{x1} and δv_{x2} near the center of the main pulse.