Simulation studies of multi-dimensional effects on electron acceleration by an oblique shock wave

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Introduction

Theory and one-dimensional (1D) electromagnetic particle simulations [1] showed that a magnetosonic shock wave propagating obliquely to an external magnetic field with a propagation speed v_{sh} close to $c\cos\theta$, where c is the speed of light and θ is the propagation angle of the shock wave, can rapidly accelerate electrons to ultrarelativistic energies. The energy of accelerated electrons increases as the external magnetic field becomes stronger. Indeed, high-energy electrons with $\gamma > 100$, where γ is the Lorentz factor, have been observed in simulations with $|\Omega_e|/\omega_{pe} > 1$, where $\Omega_e(< 0)$ and ω_{pe} are the electron gyro and plasma frequencies, respectively. In this mechanism, some electrons are trapped and energized in the main pulse region of the shock wave. The 1D electromagnetic particle simulations also demonstrated that once electrons become trapped, they cannot readily escape from the wave and are trapped deep inside the main pulse region [2].

Recently, preliminary results of two-dimensional (2D), fully kinetic, relativistic, electromagnetic particle simulations have shown [3] that after trapping and energization in the main pulse, some electrons can be detrapped from the main pulse, retaining their ultrarelativistic energies. Some of detrapped electrons have been observed to be accelerated to much higher energies by the mechanism reported in refs. [4] for accelerating relativistic ions. In this study, we investigate multi-dimensional effects on electron motions in an oblique shock wave in more detail, by 2D electromagnetic particle simulations and test particle calculations. First, the evolution of a large number of electrons is analyzed by 2D electromagnetic particle simulation. Next, we calculate the motion of the same number of test electrons in the electromagnetic fields averaged along the shock front. A comparison of the orbits of the two groups of electrons clearly verifies that electron detrapping is caused by 2D electromagnetic fluctuations along the shock front.

Simulation

We carry out a shock wave simulation with a two-dimensional (two spatial coordinates and three velocity components) relativistic electromagnetic particle code with full ion and electron dynamics. The simulation plane is (x, y) of $L_x \times L_y = 16384\Delta_g \times 128\Delta_g$ size, where Δ_g is the grid spacing. The simulation system is periodic in the y-direction and bounded in the x-direction; the plasma particles are confined in the region $200\Delta_g < x < (L_x - 200\Delta_g)$, being specularly reflected at these boundaries. The total number of simulation particles is $N \simeq 1.1 \times 10^9$.

We follow the orbits of 2.1 $\times 10^6$ electrons in the above 2D electromagnetic particle simulation. We call these 2Ds electrons. We also compute the orbits of the test particles by integrating the relativistic equation of motion,

$$\frac{d\boldsymbol{P}}{dt} = -e\bar{\boldsymbol{E}}(x,t) - \frac{e}{c}\boldsymbol{v} \times \bar{\boldsymbol{B}}(x,t). \qquad (1)$$

Here, $\bar{\boldsymbol{E}}(x,t)$ and $\bar{\boldsymbol{B}}(x,t)$ are the y-averaged fields of $\boldsymbol{E}(x,y,t)$ and $\boldsymbol{B}(x,y,t)$, respectively, obtained in the 2D electromagnetic particle simulation. In eq. (1), 2D electromagnetic fluctuations along the shock front are excluded.

We denote the test particles that follow eq. (1) as 1Dt electrons. The number of 1Dt electrons is 2.1×10^6, which is equal to the number of 2Ds electrons. The initial positions and velocities of 1Dt electrons are exactly the same as those of 2Ds electrons. The 2D electromagnetic fluctuations are included in the calculation of the motions of 2Ds electrons, whereas they are excluded in the calculations of 1Dt electrons. A comparison between the orbits of 2Ds and 1Dt electrons can elucidate the effects of 2D fluctuations on electron motion in an oblique shock wave.

The ion-to-electron mass ratio is $m_i/m_e = 400$. The light speed is $c/(\omega_{\rm pe}\Delta_g) = 4.0$ and the electron and ion thermal velocities in the upstream region are $v_{\rm Te}/(\omega_{\rm pe}\Delta_g) = 0.5$ and $v_{\rm Ti}/(\omega_{\rm pe}\Delta_g) = 0.025$, respectively. The external magnetic field in the (x,z) plane is $\boldsymbol{B}_0 = B_0(\cos\theta, 0, \sin\theta)$ with $\theta = 54^\circ$. The ratio of the electron gyro frequency to the plasma frequency is $|\Omega_{\rm e}|/\omega_{\rm pe} = 5.0$ in the upstream region. We simulate a magnetosonic shock wave propagating in the x-direction with a speed $v_{\rm sh} \simeq 0.95c\cos\theta$ and the Alfven Mach number $M_{\rm A} = 2.3$; these values are close to those in previous 1D particle simulations [1, 2] where deep electron trapping was observed.

Figure 1 shows the electron phase space plots (x,γ) and profile of B_z at $\omega_{\rm pe}t = 3360$, where γ is the Lorentz factor and the value of B_z is averaged over the y direction. In the upper panel, some of 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 region to the downstream region. After trapping in the main pulse region, some 2Ds electrons are detrapped from it, retaining their high energies. The maximum energy of 2Ds electrons reaches $\gamma \sim 800$, which is higher than that of 1Dt electrons, $\gamma \sim 400$. This indicates that some detrapped 2Ds electrons underwent enhanced acceleration by the shock wave.

Figure 2 shows the time variations in γ and the position $x - x_m$ of a 2Ds electron (black solid line) and a 1Dt electron (gray dashed line), where x_m is the position where B_z has its peak. The

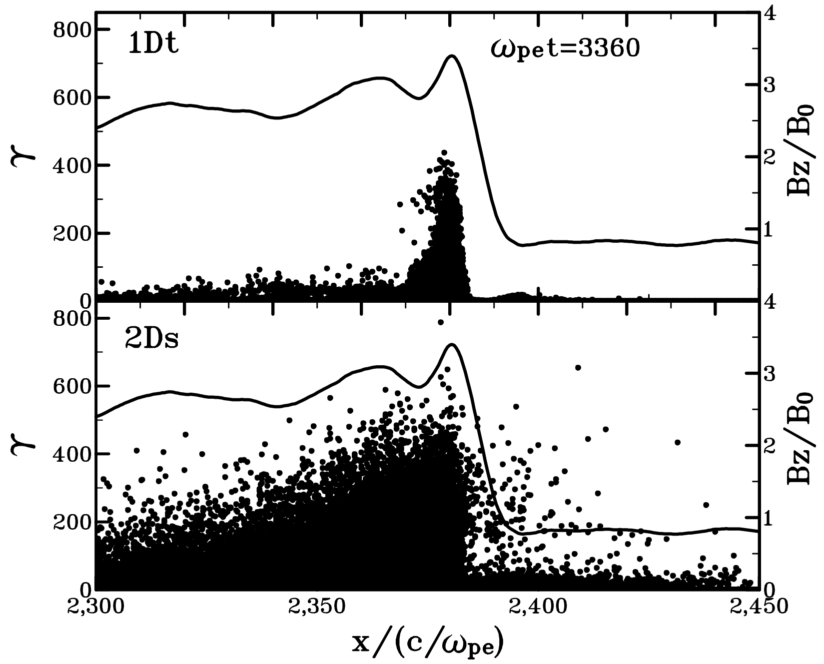

Figure 1: Phase space plots (x, γ) of 1Dt and 2Ds electrons, and the magnetic field profile at $\omega_{\rm pe}t = 3360$. The values of B_z are averged along the y direction.

initial velocities and positions of 2Ds and 1Dt electrons are the same. The lower panel shows that both 1Dt and 2Ds electrons are reflected near the end of the main pulse at $\omega_{\rm pe}t \simeq 250$ and are then trapped in the main pulse region. However, after that, the orbits of the two electrons are completely different. The 1Dt electron continues to be trapped in the main pulse region, whereas the 2Ds electron is detrapped from the main pulse and escapes to the upstream region. The 2Ds electron then crosses the shock front several times because of gyromotion with its large gyroradius. The upper panel shows that the 1Dt electron is accelerated to $\gamma \sim 100$ at $\omega_{\rm pe}t \simeq 1000$. After $\omega_{\rm pe}t \simeq 1000$, its γ oscillates with a time period $\omega_{\rm pe}t \sim 1000$; γ increases (decreases) when the position x is $x < x_m$ ($x > x_m$). Unlike the γ of the 1Dt electron, the γ of the 2Ds electron increases continuously on an average. During the period from $\omega_{\rm pe}t \simeq 500$ to 2300, the 2Ds electron stays near the center of the main pulse. Its γ becomes $\gamma \simeq 300$ at $\omega_{\rm pe}t \simeq 2000$. At $\omega_{\rm pe}t \simeq 2500$, the 2Ds electron escapes to the upstream region with an ultrarelativistic energy. It then moves in and out of the shock wave because of gyromotion. The electron gains energy from the transverse electric field E_y when it is in the shock wave because the gyromotion is antiparallel to E_y; in the laboratory frame, E_y is positive in the shock wave and almost zero in the upstream region. As a result of this process, γ increases stepwise after $\omega_{\rm pe}t \simeq 2300$. (The small dips of γ are due to E_x at the shock front).

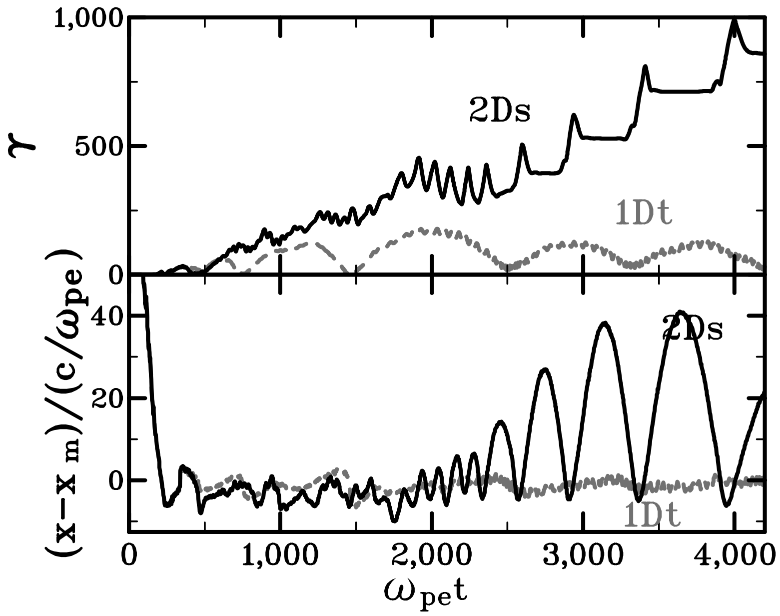

Figure 2: Time variations in γ and the positions $(x-x_m, y, z)$ of a 1Dt and a 2Ds electrons.

Summary

We studied the effects of electromagnetic fluctuations with finite wave numbers along the shock front on electron motion in an oblique shock wave. First, we performed a shock wave simulation using a two-dimensional electromagnetic particle code assuming that a shock wave propagates in the *x*-direction, following the orbits of a large number of electrons. Next, we calculated the motion of the same number of test electrons in the *y*-averaged electromagnetic fields obtained from the 2D simulation; that is, in the equation of motion of the test electrons, 2D electromagnetic fluctuations are excluded. A comparison between the former simulation electrons (2Ds electrons) and the latter test electrons (1Dt electrons) elucidated the multidimensional effects on the trapping and acceleration of electrons in an oblique shock wave.

References

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