Electron accelerations at high Mach number shocks: Two-dimensional Particle-in-Cell simulations on massively parallel supercomputer systems

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1 Introduction

Plasma kinetic processes at collision-less shocks have been investigated and recognized as important for injecting electrons towards so-called the diffusive shock acceleration mechanism. The shock surfing acceleration is one of the prominent mechanisms that can quickly accelerate the electrons at the leading edge of the shock foot region by DC electric fields. The underlying mechanism of the shock surfing acceleration is the plasma kinetic process between the reflected ions and the incoming electrons that leads to the excitation of Buneman instability. Numerical investigations of the shock surfing acceleration have been reported by Partile-in-Cell (PIC) simulation which follows particles motions with the electromagnetic field development self-consistently. Recently, two-dimensional PIC simulation studies reported contrary results: [1] reported the shock surfing acceleration is effective in a high Mach number perpendicular shock evolution while it is not a dominant process or even not observed in the other PIC simulation results [2, 3]. In this paper, we report PIC simulation results of the electron acceleration at high Mach number perpendicular shocks. The dependence of the acceleration mechanism on the ion to electron mass ratio and the Alfven Mach number is discussed.

2 Numerical method

We have examined shock evolutions by a two-dimensional Particle-in-Cell simulation code. The code solves ion and electron motions along with the electric and magnetic fields developments. The electric and magnetic fields are solved implicitly for stability. The calculation of the current density is based on a charge conservation scheme. The code is parallelized via domain decomposition by using Message Passing Interface (MPI) library and OpenMP and runs efficiently on massively parallel supercomputer systems (Figure 1).

The shock is formed by injecting particles from the boundary on the left-hand side ($x = 1$) and reflecting particles at the boundary on the right-hand side ($x = L_x$). The injected plasma carries a z-component of the magnetic field and thus the convective electric field $E_y = V_x B_z$ (perpendicular shock). The periodic boundary conditions are applied at $y = 1$ and L_y. The simulation box sizes in the x and y directions are $L_x = 10V_0/\Omega_{gi}$ and $L_y = 5\lambda_i$, respectively, where V_0 is the upstream speed, Ω_{gi} is the ion gyro frequency, and λ_i is the ion inertia length in the upstream region. The grid size Δh is set equal to Debye length in the upstream region.

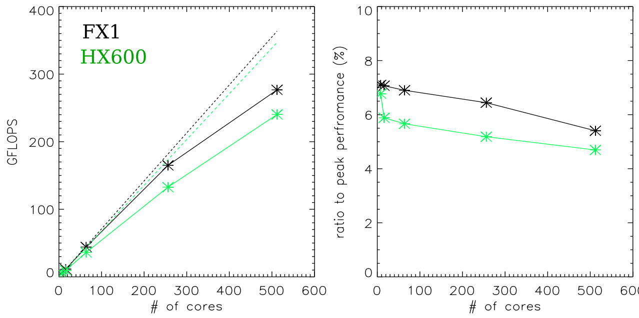

Fig. 1. (Left) Performance of the PIC code in GFLOPS vs. number of processor cores. Solid and dashed lines with symbols are the obtained results for Fujitsu FX1 and Fujitsu HX600, respectively. The straight lines indicate 100% efficiency of the parallelization. (Right) Efficiency of the performance vs. number of processor cores.

We have examined several runs with various ion to electron mass ratios (M/m) and the Alfven Mach numbers (M_A), while the upstream electron β_e and the ratio of the electron plasma to gyro frequencies ω_{pe}/Ω_{ge} are fixed to $\beta_e = 0.5$ and $\omega_{pe}/\Omega_{ge} = 10.0$ among the simulation runs. The mass ratio varies from 25 to 100 and the Alfven Mach number is increased from 15 to 30 for the $M/m = 100$ case. The upstream parameters are summarized in Table 1. The maximum computational resource (Run C) are used with 24001x1024 grid points in which 5×10^9 particles motions are solved with 512 processor cores on Fujitsu FX1 supercomputer system at JAXA.

3 Results

The maximum energy gain of electrons was found in Run C in which the electrons are accelerated at the edge of the foot by the shock surfing acceleration. When a particle entered the unstable region of the Buneman instability, it is accelerated by the convective electric field while being

Table 1. Upstream parameters

	M/m	M_A	V_0/c	β_e	ω_{pe}/Ω_{ge}
Run A	25	15	0.2	0.5	10
Run B	100	15	0.1	0.5	10
Run C	100	30	0.2	0.5	10

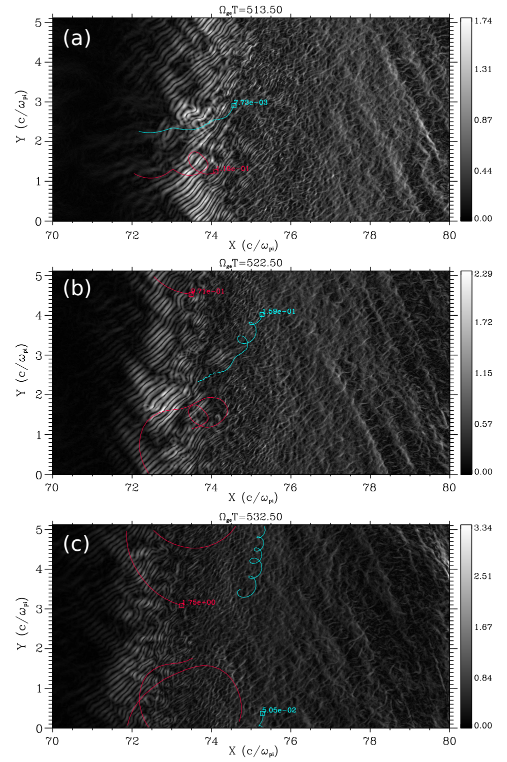

Fig. 2. Trajectories of accelerated (red) and non-accelerated (cyan) electrons superposed on the two-dimensional profile of the electrostatic field strength. Open square locates the position of the particle at each time step following the trajectory back for 15 Ω_{ge}^{-1}. A number located beside the open square denotes $\gamma - 1$. Snapshots are taken at times of (a) $\Omega_{ge}T = 513.5$, (b) $\Omega_{gi}T = 522.5$, and (c) $\Omega_{gi}T = 532.5$, respectively.

captured by the electrostatic potential. The present two-dimensional simulation shows in Figure 2(a) that a sampled electron can be escaped from the potential well at a time after gaining a fraction of energy and drifts toward the downstream. Since the length of the potential well is limited to the order of the ion inertia length, the particle can escape from the well even though the electric field strength is sufficiently large. This is the multi-dimensionality effect. Nevertheless it can enter the unstable region from the downstream-side again since the gyro radius of the accelerated particle becomes larger than before. Then the second surfing acceleration is realized. In the trajectory in Figure 2(b), the energy gain is more effective than in the previous encounter, and the energy reached $\gamma \sim 2$. The third encounter with the unstable region is possible in the same manner, and the energy is increased to $\gamma \sim 3$ (Figure 2(c)). For accelerated particles, they typically experience the shock surfing acceleration three times as shown in this example. The present acceleration mechanism can be applied to lucky particles that will constitute the non-thermal population, and most of the particles that will constitute the thermal population drift toward the downstream without being captured as shown with cyan lines in Figure 2. Nevertheless the shock surfing acceleration is so effective as it can energize the electrons from $\gamma \sim 1$ to the relativistic regime of $\gamma \sim 3$ within a time scale of $\sim 20\ \Omega_{ge}^{-1}$, or $\sim 0.2\ \Omega_{gi}^{-1}$ in this particular case with $M/m = 100$.

Figure 3 shows the electron energy spectra obtained in the downstream for three simulation runs (Table 1). The energy spectrum in Run C exhibits a high energy tail which deviates from the thermal population and reaches $\gamma \sim 9$. A similar non-thermal electron production is observed in Run A in which the Buneman instability is highly activated at the edge of the foot as well. A significant reduction of the maximum energy of the electron was observed in Run B as we increased the mass ratio from 25 to 100 while M_A is fixed to 15. This trend is consistent with the recent two-dimensional simulation study [2].

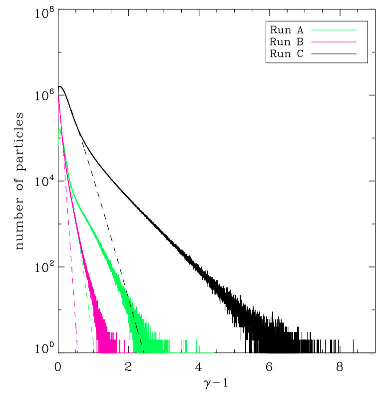

Fig. 3. Energy spectra of the electron in the downstream region. The results are compared for (a) Run A (green), Run B (magenta), and Run C (black). Dashed lines are fitted Maxwell distributions.

4 Summary

We have examined electron acceleration mechanisms at high Mach number shocks by means of two-dimensional Particle-in-Cell (PIC) simulations with various ion-to-electron mass ratios, Alfvén Mach numbers. We found electrons are effectively accelerated at a super-high Mach number shock ($M_A = 30$) with a mass ratio of $M/m = 100$ and $\beta_e = 0.5$. The electron shock surfing acceleration is found out to be an effective mechanism for accelerating the particles toward the relativistic regime even in two dimensions with the large mass ratio. Buneman instability in the super-high Mach number shock resulted in a coherent electrostatic potential structure which enabled an efficient trapping of the electrons. While multi-dimensionality allows the electrons to escape from the trapping region, they can interact with the strong electrostatic field several times. This multiple interaction enables effective shock surfing accelerations as has been found in the small mass ratio case.

Acknowledgement

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References

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