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Large-scale Particle-in-Cell simulations of electron accelerations at high Mach number collision-less shocks

超並列版電磁プラズマ粒子コードによる高マッハ数無衝突衝撃波における電子加速

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Electron accelerations at high Mach number (M_A>15) collision-less shocks are presented by examining two-dimensional electromagnetic Particle-in-Cell simulations on massively parallel supercomputer systems. For an increased ion to electron mass ratio (M/m=100) case, the simulation of the high Alfven Mach number (M_A~30) shock resulted in production of accelerated electrons in the shock foot region where large amplitude electrostatic waves are excited by the reflected ions and incoming electrons. The acceleration mechanism of the electrons are presented with various M/m and M_A cases

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 examine the shock evolution 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) and OpenMP librarlies. The code is efficiently parallelized up to 512 processor cores (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 $E_y=-\mathbf{V}\mathrm{x}\mathbf{B}|_y$ (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 $L_x=10\ v_0/\Omega_{gi}$ 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. The grid size Δh is set equal to Debye length in the upstream region.

We have examined several runs with various ion to electron mass ratios (M/m) and the Alfven Mach numbers (M_A), while the upstream β and the ratio of the electron plasma to gyro frequencies ω_{pe}/Ω_{ge} are fixed to β=0.5 and ω_{pe}/Ω_{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 (Run3) are used

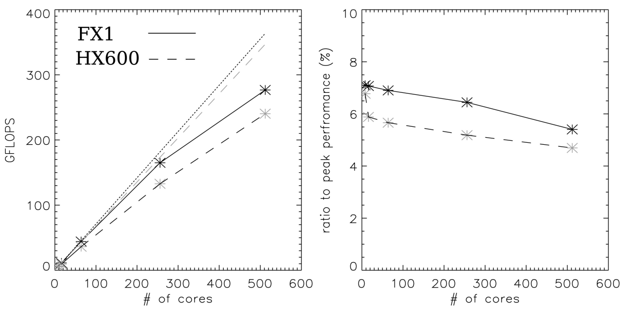

Figure 1: (Left) Performance of the PIC code in GFLOPS vs. number of processor cores. Solid and dashed lines with symbols are the obtained results for Fujitsu FX1 and Fujitsu HX600, respectively. The straight lines indicate the 100% efficiency of the parallelization. (Right) Efficiency of the performance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

with 24001x1024 grid points in which 10^{10} particles motions are solved with 512 processor cores on Fujitsu FX1 supercomputer system at JAXA.

3. Results

Figure 2 shows the electron energy spectra obtained in the foot and downstream regions of the shock for three simulation runs (Table 1). In all simulation runs, clear differences in the spectra are not observed between in the foot and downstream regions.

By comparing Run1 with Run2, we see a clear reduction of the maximum energy of the electron as we increased the mass ratio from 25 to 100 while M_A is fixed to 15. This tread is consistent with the recent two-dimensional simulation study [2].

For M/m=100 case, we have also examined the case with M_A=30 (Run3) and compared with the lower M_A case (Run2). We have found that even for the large M/m case, the high Mach number of 30 can produce much more high energy particles than lower M_A case, even more efficiently than in Run1. The energy of the electron reaches up to γ~7

Table I. Upstream parameters

	M/m	M_A	v0/c	β	ω_{pe}/Ω_{ge}
Run1	25	15	0.2	0.5	10
Run2	100	15	0.1	0.5	10
Run3	100	30	0.2	0.5	10

4. Summary

We have examined high Mach number (M_A>15) collision-less shocks in order to investigate electron accelerations by the shock surfing acceleration mechanism. Contrary to the previous results that the shock surfing acceleration mechanism in large M/m

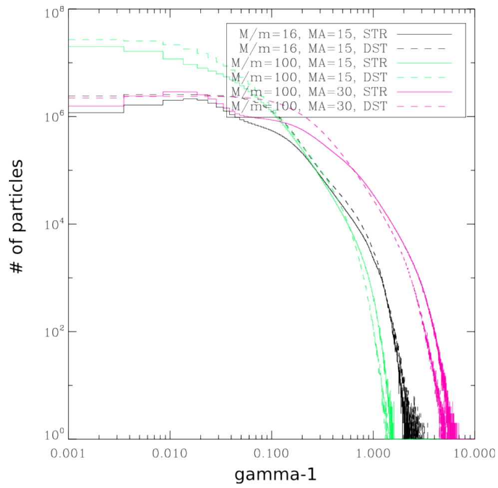

Figure 2: Energy spectrum of the electron in the foot (solid) and the down stream (dashed) regions of the shock. The energy spectra are shown for Run1 (black), Run2 (green) and Run3 (magenta).

cases is not important, we have found an efficient acceleration of the electrons in the M/m=100 case with M_A=30. Thus for larger M/m case, a large M_A shock is required for large amplitude of the instability that efficiently accelerates the electrons.

Acknowledgments

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