3D PIC simulations of high-Mach-number shocks and associated electron accelerations

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We examined 3D PIC simulations of quasi-perpendicular, high-Mach-number shocks. We successfully followed a long-term evolution in which two different acceleration mechanisms coexist in the 3D shock structure.

The Buneman instability is strongly excited ahead of the shock front in the same manner as have been found in 2D simulations. The surfing acceleration is found to be very effective in the present 3D system.

In the transition region, the ion-beam Weibel instability generated strong magnetic turbulence in 3D space. Energetic electrons, which initially experienced the surfing acceleration, undergo the shock drift acceleration while being scattered by interacting with the turbulent fields. This pitch-angle scattering allowed the energetic particles stay in the upstream regions much longer than classical estimates from the adiabatic theory.

Simulation runs for super-luminal cases resulted limited acceleration efficiency. Therefore, the present mechanism works essentially in non-relativistic quasi-perpendicular shocks, but with wide range of the upstream magnetic field obliquity. We have also confirmed that systems (1D and 2D) lacking either the SSA or the Weibel turbulence could not lead to production of very high energy particles.