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Electron Accelerations at High-Mach-Number Collision-less Shocks

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Elucidating acceleration mechanisms of charged particles have been of great interests in laboratory, space, and astrophysical plasmas. Among other mechanisms, a collision-less shock is thought as an efficient particle accelerator. The idea has been strengthened by radio, X-ray, and gamma-ray observations of astrophysical objects such as supernova remnant shocks, where it has been indicated that protons and electrons are efficiently accelerated to TeV energies at such very strong shock waves. Efficient electron accelerations at high-Mach-number shocks was also suggested recently by in-situ measurements at the Saturn's bow shock. Motivated by these circumstances, laboratory experiments using high-power laser facilities emerge to provide a new platform to tackle these problems.

The diffusive shock acceleration (DSA) theory has provided a solution to observational evidences for efficient accelerations at collision-less shocks, as it predicts a power-law energy spectrum of particles having a spectral index that is close to the values suggested by multi-wavelength observations. As the DSA theory presumes pre-existing mildly energetic particles, pre-acceleration mechanisms are required to provide a seed population for DSA, particularly for electrons. The connection between pre-acceleration and DSA remains a critical issue in shock acceleration theory.

Numerical simulations have revealed that electrons can be efficiently heated and accelerated in high Mach-number perpendicular shocks. So-called the shock surfing acceleration mechanism uses large-amplitude electrostatic waves generated by the Buneman instability at the leading edge of the shock. Recently, Matsumoto et al. [2015] proposed a stochastic acceleration mechanism by turbulent reconnection in the shock transition region through excitation of the ion Weibel instability.

In order to deal with the two different acceleration mechanisms in a self-consistent system, we examined 3D PIC simulations of a quasi-perpendicular, high-Mach-number shock. We successfully followed a long-term evolution in which two different acceleration mechanisms coexist in the 3D shock structure (Figure 1).

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.

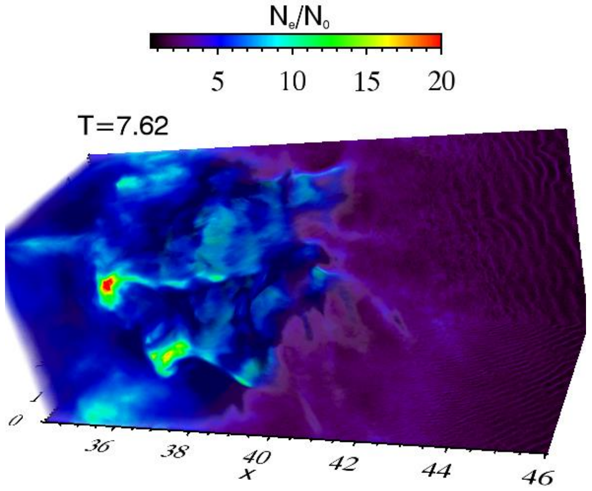

Figure 1: Electron density profile in a fully-developed stage. Electron-scale Buneman mode (x~45) and ion-scale Weibel mode (36 < x < 44) coexist in the high-Mach-number quasi-perpendicular shock.

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. Another mechanism associated with magnetic reconnection in the Weibel turbulence (Matsumoto et al., 2015) was not observed here because the Mach number was not large enough (as also confirmed by 2D simulations with the same parameters). Nevertheless, this process may also come into play at even higher Mach-number shocks to boost the overall acceleration efficiency. Following the time evolution much further will eventually illuminate a whole process including self-excited low-frequency electromagnetic waves in the upstream region by the relativistic electrons and their subsequent participation in the DSA cycle in high Mach-number quasi-perpendicular shocks.