# Fast electrons at slow shocks

## Microphysics of slow collisionless shocks in nonthermal sources of radiation

***A. Bohdan, M. Pohl, T. Teschke, P. J. Morris**, Institut für Physik und Astronomie, Universität Potsdam*

### In Short

- We conduct kinetic simulations of non-relativistic shocks to study the acceleration of electrons at supernova remnants
- Our main objective is to establish whether or not our understanding of electron acceleration at mildly relativistic shocks also applies to shocks with realistic velocities.
- Our simulations are scientifically important because they address the unsolved problem of electron injection. It is vital that we understand this critical ingredient in the theory of particle acceleration at shocks because it determines the level of cosmic-ray feedback and hence the nonlinearity of the system.

Deciphering the acceleration mechanisms of charged particles is essential to our understanding of many physical phenomena and of high interest in astroplasma physics. It is widely accepted that shocks, such as those formed by the interaction of supernova ejecta with the interstellar medium, can efficiently accelerate charged particles. The presence of freshly accelerated electrons is inferred by the association of radiation at radio, X-ray, and $\gamma$-ray frequencies to shocks. It is usually assumed that these particles are accelerated by diffusive shock acceleration. Here, electrons undergo repeated shock crossings and gain energy each time. However, this picture is not yet complete, with a crucial unsolved problem that of particle injection. For diffusive shock acceleration to operate, particles must see the shock as a sharp discontinuity in the plasma flow. In reality, the shock has a finite width though that is commensurate with the gyroradius of the incoming ions. The comparatively small electron mass, and therefore gyroradius, necessitates some pre-acceleration with a large energy gain to increase their gyroradii before they can be accelerated further.

Energetic charged particles couple to their environment through electromagnetic turbulence that is partially self-produced. We conduct large particle-in-cell (PIC) simulations of collisionless shocks with a view to elucidate the processes that provide electron acceleration. PIC simulations are the appropriate tool to study particle injection into shock acceleration because injection at collisionless shocks is a kinetic problem that cannot be addressed with MHD or other fluid techniques. PIC simulations alone can track the impact of electron-scale fluctuations on the ion dynamics through self-consistent treatment of both electrons and ions. Three-dimensional studies can currently be conducted only with low resolution and for very idealized parameters [1], and so we concentrate on two-dimensional simulations.

We study electron pre-acceleration for conditions at young-supernova-remnant shock waves, but the results are applicable to any high-Mach-number non-relativistic perpendicular shock, e.g. the bow shock of Saturn [2]. A number of mechanisms are responsible for electron acceleration in the shock transition. The electrostatic Buneman instability is excited if the thermal velocity of the cold upstream electrons is smaller than the relative speed between incoming electrons and reflected ions, and is illustrated in Figure 1b. Shock surfing acceleration occurs when electrons are accelerated by these waves [3]. Magnetic reconnection (Figure 1b) in the shock ramp results in acceleration of electrons via a number of channels discussed in [4]. Electrons also undergo stochastic Fermi-like acceleration [5].

We have previously studied the efficiency of shock-surfing acceleration for a variety of simulation setups and physical parameters. The energy gain always arises from the electrostatic field of a Buneman wave with which the electron travels for some time [6].

We recently showed that the relative contribution of each electron pre-acceleration mechanism was independent of the shock velocity [7], yet our earlier results from this project indicate preferential heating of electrons over ions for our slowest simulated shock velocity of $v_{\rm sh} \sim 0.05c$. We have already established the importance of the Buneman instability regarding electron acceleration via shock-surfing acceleration, therefore it is crucial that it is properly captured in our simulations. This is challenging because the Buneman instability occurs on spatial scales proportional to the velocity difference between the incoming electrons and reflected ions that cause it, which in turn is proportional to the shock velocity. Thus we need to resolve smaller scales in our slow shock simulations, which is computationally demanding.

It is therefore possible that our simulation resolution needs to be increased for slow shock simulations to properly resolve the Buneman instability or any additional small-scale structures. These could otherwise cause numerical heating or modify the

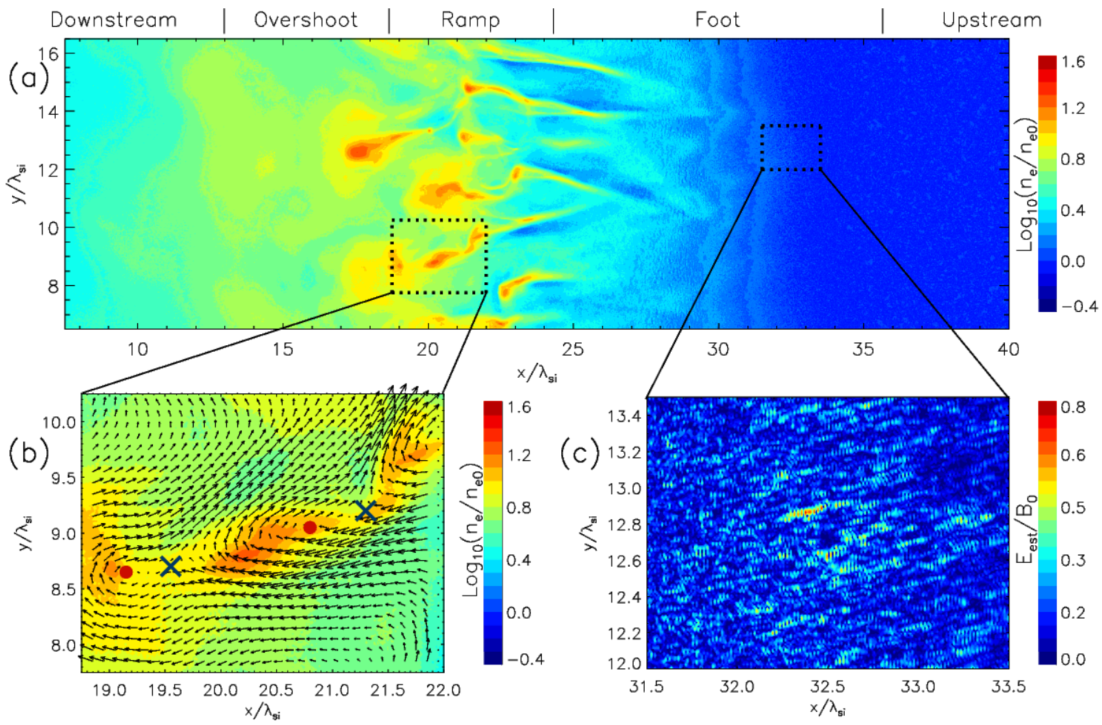


***Figure 1:*** *The structure of a slow ($v_{\rm sh} = 0.053c$) shock with in-plane magnetic field configuration. (a) shows the electron density relative to the original upstream density, while (b) and (c) show magnified views of magnetic reconnection and Buneman waves, respectively.*

physical behaviour of electrons at the shock. We therefore wish to explore the effect of employing a higher resolution on electron heating for slow shock simulations.

These simulations are necessary to address our main question of whether or not our understanding of electron acceleration at mildly relativistic shocks also applies to shocks with realistic, physically motivated, velocities. In detail, our objectives are:

- Does the simulation resolution need to be increased in order to properly capture the Buneman instability for slow shocks?
- Can an insufficient simulation resolution produce numerical heating effects, or otherwise modify the physical behaviour of particles at the shock?
- Can we resolve new sub-structures present in the shock foot for higher-resolution simulations of slow shocks?
- What is the effect on the obliquity angle on the structure of a slow shock and how does it influence the instabilities present in the transition region? Does such a shock behave in the same way as those with faster shock velocities?
- For oblique slow shocks, what is the rate of reflected electrons? What is their energy distribution and how do they modify the region upstream of the shock?

## WWW

http://www.physics.uni-potsdam.de/index.php

## More Information


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## Project Partners

J. Niemiec, A.Ligorini; IFJ PAN Cracow, Poland