# Kinetic studies of nonrelativistic parallel shocks

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**Abstract:** Shock acceleration relies on the presence of magnetic field fluctuations that can scatter relativistic charged particles in the shock vicinity. We report on kinetic particle-in-cell studies of non-linear evolution of magnetic turbulence that arises upstream of the shock as well as at the shock itself. We will in particular address the relation between modes seen in the simulations and waves expected from a linear instability analysis, the efficiency of small-scale turbulence in scattering relativistic particles, and the feedback of high-energy particles on the microscopic instabilities that govern the formation of a shock. First results of large-scale PIC simulations of nonrelativistic unmagnetized and magnetized parallel shock formation and particle acceleration will also be presented.

**Keywords:** acceleration of particles, cosmic rays, shock waves, magnetic turbulence, numerical methods

## 1 Introduction

The ubiquitous presence in the Universe of very energetic charged particles called cosmic rays implies the existence of powerful particle accelerators. In the Milky Way galaxy supernova remnants (SNRs) have long been thought to be those accelerators, and now they are believed to host not only powerful particle-acceleration processes, but also very efficient turbulent magnetic-field amplification. Generally, both processes are associated with shocks - sudden jumps in density and temperature that arise in fast outflows of plasma. In fact, the generation and amplification of cosmic magnetic fields by kinetic instabilities of anisotropic particle distributions in fully and partially ionized plasmas is relevant for many cosmic sources including cosmological seed magnetic fields and powerful outflow sources such as solar flares, stellar and galactic winds, pulsar-wind nebulae, supernova shock waves, and the relativistic jets of active galactic nuclei (AGN) and gamma-ray burst (GRB) sources.

We use Particle-in-Cell simulations to self-consistently model the evolution, saturation, and feedback of plasma instabilities in a variety of environments.

## 2 Cosmic-ray streaming instabilities

The forward shocks of young shell-type supernova remnants may be efficient acceleration sites for Galactic cosmic rays via the mechanism of diffusive shock acceleration, which requires turbulent, amplified magnetic fields in the shock's upstream region. The confinement may be supplied to some degree by the interstellar magnetic field, but the estimated upper limit in energy falls short of what is observed in cosmic rays of Galactic origin. The implied need for a much stronger, turbulent upstream field, together with observational evidence for strong magnetic fields immediately behind the forward shock, has attracted attention to the question of upstream magnetic-field amplification. It is well known that ion beams can generate magnetic turbulence via resonant and non-resonant interactions [13]. Bell [1] suggested that nonresonant magnetic-field amplification may also be caused by the cosmic-ray current expected in the cosmic-ray precursor of a quasi-parallel shock. Although substantial field amplification has occurred in magnetohydrodynamical (MHD) simulations that assume a constant cosmic-ray current [1, 14], the approximations of MHD may not be appropriate for modeling the nonlinear evolution and eventual saturation of this instability; we must use kinetic methods to simulate these later stages with accuracy, including any backreaction on the cosmic rays.

Our earlier work [7] used two-dimensional and three-dimensional PIC simulations to model the growth and saturation of a current-driven instability. We relaxed the condition assumed in the calculations of [1] that the rate of unstable growth must be much less than the ion gyrofrequency, and we found that an oblique filamentary mode dominated the initial magnetic-field growth. Riquelme and Spitkovsky [10] confirmed the findings and in particular investigated the parameters for the transition between the filamentation mode seen in the early simulations and the parallel-wave mode seen in the MHD simulations, and verified that the parallel mode appears only in the regime with $\omega < \Omega_i$. However, despite the difference in initial unstable modes, the nonlinear characteristics of the system observed in both works were similar. In particular, both investigations observed only modest amplification of the magnetic field, and saturation by the same mechanism. Analytical calculations with a kinetic treatment of the current-driven instability predict a saturation level consistent with the kinetic simulations [3].

We have further simulated the turbulent amplification of the interstellar magnetic field upstream of a nonrelativistic shock using a kinetic 2.5-dimensional particle-in-cell code. We observe the following [11]:

1. That the non-resonant streaming instability is seen initially for our choice of parameters, but with fluctuations appearing in the plasma density.

2. That the plasma quickly evolves and saps the bulk momentum from the drifting cosmic rays.

3. The reduction of relative drift effectively removes the cosmic-ray current and saturates the magnetic-field amplification to $\sim 20\, B_{0,\parallel}$.

4. This saturation mechanism is independent of the initial linear instability, occurring as a result of the back-reaction on the cosmic rays.

5. Strong transverse plasma motions arise in conjunction with the turbulent magnetic field exceeding the homogeneous background field, which result in 2nd-order Fermi acceleration.

6. Interactions between differently-moving plasma parcels give rise to significant fluctuations in density and temperature of the upstream interstellar medium.

7. The plasma begins to drift, suggestive of a cosmic ray-modified shock, until its speed approximately matches that of the cosmic-ray population.

8. The phase-space distribution of cosmic rays undergoes significant changes: the development of anisotropy within the population rest frame beginning during the linear growth of the magnetic field, and decrease in bulk speed associated temporally with the saturation of the magnetic field.

## 3 Beam-driven instabilities

In the previous section we have discussed a system in which a population of CRs slowly drifts relative to the upstream plasma We have also studied the interaction of a cold, relativistic ion beam penetrating a cold plasma composed of electrons and ions using 2.5-D PIC simulations, complemented with a linear analysis of the dispersion relation for linear waves with arbitrary orientation of $\vec{k}$, for parameters that permit the growth of nonresonant, purely magnetic parallel modes [8]. We observe a close competition of the nonresonant mode with the filamentation instability and Buneman modes, which is also evident in the linear dispersion relation. The specific choice of parameters determines which of the three modes of instability dominates. In some cases, filamentation is initially important and modifies the later evolution of the parallel nonresonant mode. As in the case of drifting CRs and nonrelativistic beams, the saturation of the magnetic-field growth proceeds via bulk acceleration. For mildly and ultrarelativistic beams, the instability saturates at field amplitudes a few times larger than the homogeneous magnetic field.

Interesting is that the magnetic field amplified via nonresonant interactions between the CR beam and the plasma can efficiently scatter CRs even for moderate field amplification levels (see Figure 1). The scattering mean free path is compatible with Bohm diffusion. Sub-Bohm diffusion was observed in Monte Carlo simulations of particle transport in the nonlinear turbulent magnetic field generated in the nonresonant instability by [9]. In that work, parallel and perpendicular diffusion coefficients were calculated by probing the spatial displacement of test particles in a static snapshot of the amplified magnetic field that resulted from MHD simulations of the instability. Here, we estimate the isotropic spatial diffusion coefficient by probing the evolution of the angular distribution of particles in the self-excited, non-stationary (growing) turbulence whose typical wavelength is at least a factor of a few smaller than the gyroradii of CRs.

## 4 Cosmic rays and shock-forming instabilities

Motivated by an interest in possible effects of cosmic rays on the physics governing the development of collisionless astrophysical shocks, we have performed several 2.5D PIC simulations of counterstreaming plasmas with various density ratios and magnetic-field strengths, both with and without a background population of energetic cosmic rays. Before cosmic rays are added to the picture, the system resembles the subject of numerous beam-plasma or interpenetrating-plasmas studies, where the initial behavior of the system can be understood in terms of known instabilities. Most prominently, the counterstreaming electron populations are the first to interact, via symmetric or asymmetric two-stream instabilities, as seen in, e.g., [6, 4]. In particular, the three-dimensional simulations of unmag-

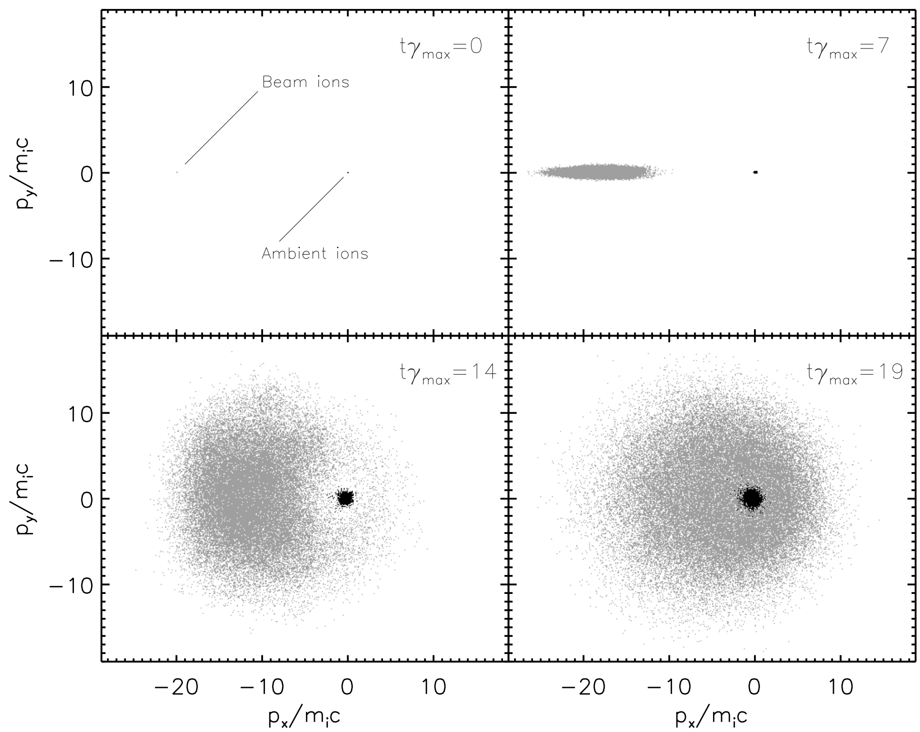


Figure 1: Phase-space distributions of the ions in the CR beam (gray) and the ambient plasma (black) at $t \cdot \gamma_{\max}$ = 0, 7, 14, and 19 for the run with $\gamma_{\rm CR} = 20$ and $v_A = c/20$.

netized electron-ion plasma collisions [4] demonstrate the formation of merging and growing current filaments in first the electrons and subsequently the ions, and the nuanced relationships among the various populations.

When we compare the system evolution in the presence of cosmic rays with that in their absence, we find that for the physical configurations studied, cosmic rays do not introduce a statistically significant departure from the unperturbed results [12]. This may be a consequence of the comparatively large mean free path and characteristic time scale for evolution of the cosmic-ray distribution: even with the amplification of electric and magnetic fields within the transition layer, cosmic rays of modest energy apparently do not couple to the dynamics of thermal electrons and ions in any appreciable way. We surmise that at least for unmagnetized or parallel shocks, the impact of cosmic rays even when their energy density is unusually large on the instabilities mediating the shock transition is negligible.

## 5 Non-relativistic shocks

Nonrelativistic collisionless shocks play an important role in SNRs, in particular in the context of particle acceleration, but are still not understood from first principles. Recent results by [5] show that non-relativistic shocks can be mediated via Weibel-type short-wave instability. Therefore, we have embarked on the very-large-scale kinetic plasma simulations of the formation of nonrelativistic shocks and their long-term evolution.

A shock may be set up by imposing a conducting wall. Plasma streams onto that wall and is reflected, resulting in a shock moving back into the plasma (e.g. [5]). Alternatively, and physically more accurate, a low-density plasma can be run into a stationary or slowly moving denser plasma. In contrast to the reflection at a wall, this setup avoids assuming the existence of an infinitely sharp contact discontinuity and allows us to study the system for different stream-counterstream density ratios, temperatures, etc. Whether magnetized or not, beam-plasma systems are susceptible to a host of both electrostatic and electromagnetic instabilities. For flow-aligned wave vectors, electrostatic modes such as two-stream or Buneman are likely to grow. In the direction normal to the flow, the filamentation instability (Weibel-like) is usually excited as well. Finally, modes with wave vectors oriented obliquely are likewise unstable, so that the unstable spectrum is eventually at least two-dimensional. Which of these modes would grow fastest highly depends on the system parameters, such as relative streaming velocity, density ratio, magnetization, etc. [2]. This clearly demonstrates a need for studies using setup like ours, since the most unstable modes excited in various settings may result in completely different shock generating plasma waves.

We have performed computer experiments for unmagnetized and weakly magnetized (flow-aligned mean magnetic field) symmetric (density of the stream equal to the density of the counterstream) and asymmetric (density ratio of 0.1) collisions of cold plasma slabs for parameters corresponding to SNR forward shock conditions. We assumed the stream-counterstream relative velocity of $\sim 0.38c$, where $c$ is the speed of light, and used a reduced ion mass of $m_i = 50m_e$. The systems were evolved for more than $2{\times}10^4\omega_{pe}^{-1}$, where $\omega_{pe}$ is the electron plasma frequency. Preliminary results show a very efficient production of mainly magnetic turbulence in the shock transition region via filamentation instabilities that turns highly nonlinear in all situations studied. For the case of symmetric plasmas the contact discontinuity quickly separates electrons of the stream from the electrons of the counterstream, but it takes considerable amount of time to similarly decouple the ions. Eventually the pair of shocks with MHD-like jump conditions is formed and subsequently maintained by the ions reflected from their fronts. Such a decoupling is not as efficient for asymmetric collisions. Although filamentation-like instabilities generate ample amount of magnetic turbulence also in this case, we do not observe efficient decoupling of the more dilute plasma ion beam from the denser slab in unmagnetized conditions. For a certain magnetization level, the dilute beam excites secondary instability in the dense slab region that eventually provides the decoupling, but at the same time leads to strong deviations from the MHD-like shock structure. In all cases, strong electron heating is also observed.

Further details will be reported at the conference and in the revised version of the Proceedings.

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