Shocking, isn't it?

Collisionless shocks and turbulence in nonthermal sources of radiation

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Kurzgefasst

We use Particle-in-cell simulations to appropriately describe the kinetic interaction between turbulence and energetic particles at Shell-type supernova remnants (SNR). More specifically, we simulate particle pre-acceleration at nonrelativistic shocks, for which we use a new, clean setup that avoids electromagnetic transients. Equipped with particle-tracking capability, we will explore through a number of 2-D and 3-D simulations why particle acceleration and reconnection appear only for specific configurations and which of them persists in 3D. In 2016 we explored this question for quasi-parallel shocks, and now we extend the program to quasi-parallel shocks. These studies are scientifically interesting because the unsolved problem of injection is the most critical ingredient in the theory of particle acceleration at shocks, as it determines the level of cosmic-ray feedback and hence the nonlinearity of the system. We also launch a new line of simulations designed to explore the viability of studying Bell's instability in the laboratory. This cosmic-ray driven plasma instability could be responsible for magnetic-field amplification in many cosmic sources of energetic particles.

We use PIC simulations that follow the individual trajectories of quasi-particles and solve Maxwell's equation for the electromagnetic fields on a spatial grid. Each quasi-particle represents many real electrons or ions, so it has the same q/m, i.e. it reacts similarly to electromagnetic fields, but its charge q and mass m are much larger than those of real electrons and ions. The fundamental plasma dynamics can then be simulated with parameters not identical to those in the real plasma, but sufficiently similar to them, so one can capture the relevant physics.

We explore the micro-physics governing the coupling of energetic charged particles, amplified turbulent magnetic field, and colliding plasma flows, that determines how suprathermal particles can be injected into Fermi-type acceleration processes at collisionless shocks. After studying parallel [1] and strictly perpendicular [2] shocks, for which the large-scale magnetic field is oriented parallel and perpendicular to the flow direction, respectively, in the last year we investigated why particle acceleration, and certain processes such as reconnection, can be observed only for certain orientations of the large-scale magnetic field relative to the simulation plane.

We found that not only electron acceleration, but also the global shock structure are affected. One example is that reconnection appears primarily in simulations with in-plane field configuration. Figure 1 displays electron spectra in the downstream region for the 3 tested magnetic-field configurations. It is evident that in the out-of-plane scenario the spectrum features a bump rather than the power-law shaped tails that are observed for oblique or in-plane configuration. The acceleration efficiency is directly related to the dominant processes at the shock.

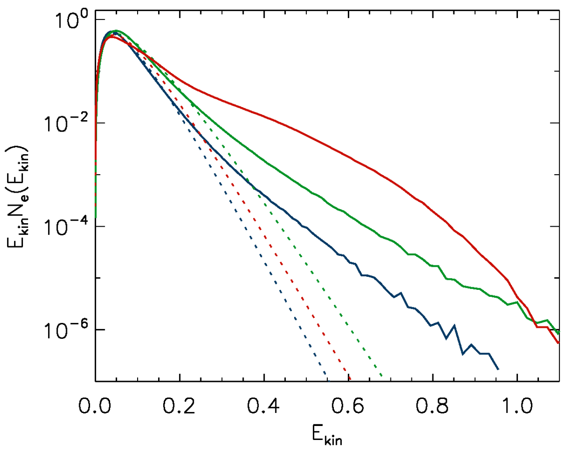

Abbildung 1: *Electron spectra in the downstream region. Dashed lines are Maxwellian fits to the downstream spectra. Blue line: in-plane magnetic field (0^o); green: 45^o; red: out-of-plane (90^o).*

For a homogeneous magnetic field oriented strictly out of plane ($\phi = 90^o$), significant shock-surfing acceleration of electrons arises when they are trapped by Buneman modes at the shock foot. The trapping condition is met in all simulation runs, but in the out-of-plane configuration the process is particularly effective. As the electrons are advected through the shock ramp, they are adiabatically heated.

For an intermediate magnetic-field configuration ($\phi = 45^o$), electron acceleration begins with trapping by Buneman modes at the shock foot. The transport of electrons is then dominated by small-scale turbulence, and further acceleration is provided by bouncing off moving magnetic structures, resembling second-order Fermi acceleration.

For a magnetic field in the simulation plane ($\phi = 0^o$) reconnection is most important. Carefully studying the trajectories of individual particles, one finds that linear acceleration in the electric field at magnetic vortices is not the only relevant process. Certainly linear acceleration provides spectacular energization of a few electrons, but trapping in vortices is important as well, as is bouncing off moving magnetic irregularities. Stochastic acceleration is further provided by turbulent contraction and expansion in the shock ramp.

We also studied the impact of the ion-to-electron mass ratio, m_i/m_e, on the efficiency of electron energization. This aspect is particularly important because 3D simulations can only be conducted with small mass ratio, on account of the computational expense. We tested 4 mass ratios between 50 and 400 and found little variation. It is important to keep the size of the simulation box equal in units of ion length scales, and to compare the number of electrons at the same time in units of the ion gyrofrequency. Figure 2 displays the fraction of suprathermal electrons for a suite of simulations with in-plane magnetic field ($\phi = 0^o$). An initial, transient spike in the number of nonthermal electrons in evident for all mass ratios, implying that simulations must be run for quite a few ion Larmor times before reliable numbers can be extracted. We also note substantial fluctuations in the nonthermal fraction after the simulation has settled. These fluctuations reflect the changes in shock structure during each reformation cycle.

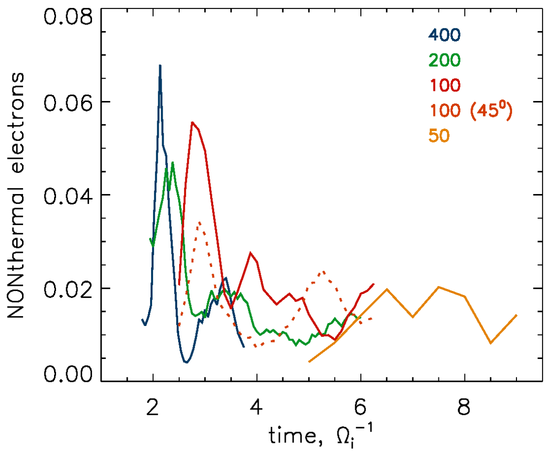

Abbildung 2: *Fraction of nonthermal electrons as function of time and for various mass ratios. For comparison, we also provide a curve for a setup with $\phi = 45^o$.*

The raw electron spectra for runs with high mass ratio extend to higher energies than do the distributions for small mass ratio. However, the electron temperature increases as well, and so the spectra have to be rescaled in units of the electron temperature. If one counts as nonthermal electrons only the particles with energy higher than a certain fixed multiple of the bulk energy, then the electron spectra look very similar, and there is no significant correlation between the mass ratio and the fraction of nonthermal electrons. We conclude that electron energization can be studied with low mass ratio.

We want to continue the PIC simulations of oblique magnetic-field configurations. All simulations shall involve particle tracking to investigate exactly where and how high-energy particle were accelerated. Again, we use our new setup that permits relatively clean simulations with perpendicular fields, and we add an additional flow-parallel magnetic-field component whose amplitude determines the angle between shock normal and large-scale magnetic field, θ_{Bn}. We will concentrate on 2D3V experiments for quasi-parallel shocks, and we plan to perform 3-D experiments for quasi-perpendicular simulations. The former is the extension to quasi-parallel shocks of our 2016 studies of quasiperpendicular shocks.

Earlier, we studied the nonlinear development and saturation processes of a nonresonant current-driven instability [3] that may be responsible for magnetic-field amplification in the precursors of shocks. We now embark on a new line of simulations designed to explore the possibility to study this important plasma instability in the laboratory. The initial idea is to use a plasma cell available at DESY in Zeuthen and an electron gun operated by the PITZ group at DESY. The plasma cell provides plasma through discharge or laser ionization with a lifetime on the order of 1 ms. The so-called dark current of the PITZ electron gun carries up to 1 mA in the form of a continuous beam of electrons with Lorentz factor $\gamma \lesssim 15$ and about 1 mm radius. With an additional magnetic field produced by Helmholtz coils the growth time of Bell's instability should be in the μs range, and many wavelengths of the mode would fit into the plasma cell.

We have to carefully simulate this scenario before a significant investment in hardware can be justified. The main issue is to avoid other instabilities that grow faster than Bell's instability. We will determine the requirements on the time profile and the angular and momentum distribution of the electron beam.

WWW

http://www-zeuthen.desy.de/~pohlmadq/

Weitere Informationen

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Förderung

DAAD, DESY DSF