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The role of electron heating in electromagnetic collisionless shock formation

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A B S T R A C T

The role of electron dynamics in the process of a collisionless shock formation is analyzed with particle-in-cell simulations, the test-particles method, and quasilinear theory. The model of electron stochastic heating in turbulent electromagnetic fields corresponding to the nonlinear stage of two-stream and Weibel instabilities is developed. The analysis of electron and field heating rates shows that the ion motion provides the energy supply for a significant continuous heating of electrons. Such a heating thus plays a role of a friction force for ions, leading to their deceleration and a shock formation.

1. Introduction

Collisionless shocks are frequent events in the interstellar medium. They can also occur in inertial fusion targets where high-energy ion beams interact with a dense expanding plasma. Understanding the process of shock formation is consequently important from a theoretical standpoint and for laboratory laser–plasma interaction experiments. Large-scale particle-in-cell (PIC) simulations are widely used to provide crucial information on the shock evolution and the energy dissipation. They also give access to ion and electron particle and energy densities and electromagnetic fields, authorizing energy transfer analysis from the ions to electrons and fields.

In this communication, we consider an interaction of two counter-propagating homogeneous sub-relativistic plasma beams with no external magnetic field applied. The deceleration of streaming ions due to the plasma instabilities is assumed to lead to a shock formation [1–3].

But the details of physical processes leading to shock formation remain unclear. In numerical simulations performed with PIC codes, three stages of evolution can be identified: the shock formation is initiated with development of the electron–ion Weibel-like micro-instability, followed by electron heating, and ion deceleration. The studies of Weibel and filamentation instabilities are the subject of experimental investigations [4] and multidimensional PIC simulations [5–7]. We here present a theoretical analysis of the instability development of two colliding plasmas and its nonlinear saturation that allows exploring the origins of the electron heating and ion deceleration. Both plasmas are assumed to be initially cold and counter-propagating with sub-relativistic velocities. The instability is characterized by analyzing the dispersion relation (plasma parameters) in the center-of-mass frame and its dependence on the electron mean energy and ion velocity. The growth rate and the characteristic scales of instability are compared to simulation results. A continuous electron heating is explained with a model of stochastic heating in fluctuating electromagnetic fields.

A detailed study of instabilities developing at the fronts of two interpenetrating plasma flows shows a rise and then a saturation of the maximum magnetic field at the time scale of a hundred electron plasma periods due to the isotropization of the electron velocity distribution [8]. But simulations with a longer time scale show that the magnetic field continues to grow up to several thousand electron plasma periods. Explaining this magnetic field secular growth is a crucial point in understanding the collisionless shock formation. Fig. 1 shows the time evolution of the longitudinal and transverse electric fields and also the magnetic field component perpendicular to the simulation plane obtained in two-dimensional (2D) PIC simulations using the same simulation parameters as in Ref. [7]. The two homogeneous plasma flows are composed of protons and electrons of density n_0 counter-propagating at the velocities $0.2c$ with respect to the center of

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mass. The magnetic field growth dominates, and a strong increase up to the level of $m_e\omega_{pe}/e$ is observed with some temporal variations. Here, m_e and e are the electron mass and charge, $\omega_{pe} = \sqrt{n_0 e^2/\varepsilon_0 m_e}$ is the electron plasma frequency, and ε_0 is the vacuum dielectric permittivity. This growth corresponds to a nonlinear evolution of the electromagnetic fields driven by the electron Weibel instability. The electron velocity distribution remains anisotropic at these long time scales as the ion streaming pulls electrons in the propagation direction. From 300 to 1200 electron plasma periods $\tau_0 = 2\pi/\omega_{pe}$, the longitudinal and transverse electric and magnetic fields have similar evolutions and values. The ions are strongly affected by the growth of the magnetic field and by the electrons dynamics. A theoretical understanding of the origins of this evolution is the main goal of this article.

Section 2 presents the results of PIC simulations of the collision of two streaming plasmas and the studies of the electron velocity distribution function. Section 3 focuses on the electron heating: a test-particle method [9] is used to evaluate the role of turbulent electrostatic and electromagnetic fields in the long-term electron heating. These results are compared with a quasilinear theory providing the estimates for the heating rate. In Section 4, we propose an “electromagnetic friction” mechanism for ion stopping, which explains our simulation results. Section 5 is dedicated to conclusions and discussions.

2. Kinetic simulations of the plasma interpenetration

The plasma collision is studied with the PIC simulations performed with the code PICLS [10] with a real electron-to-ion mass ratio covering the range of several hundred of electron plasma periods τ_0. We are interested in the electromagnetic regime of collisionless shock formation in the interaction of two relatively cold electron–proton plasmas with the temperature $T_0 = 100$ eV and the particle densities $n_0 = 10^{18}$ cm^{-3} propagating with the velocities $\pm v_0 = \pm 0.2\,c$ along the y axis, where c is the speed of light. The simulation box is 1.2 mm wide and 12.0 mm long containing 2872 × 28,672 cells with periodic boundary conditions in x direction and absorbing boundary conditions in y direction. We use 10 particles per cell and plasma profiles are smoothed at the edges to avoid artificial effects in the interpenetration region. Our simulations extend up to the instant 300 τ_0 with a numerical resolution of 80 steps per one electron plasma period. The choice of plasma density is arbitrary and is dictated by a possible experiment with a

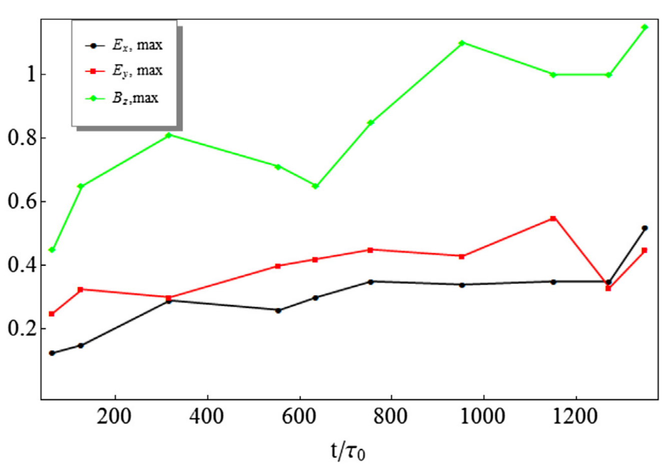

Fig. 1. Time evolution of the longitudinal (E_y) and transverse (E_x) electric fields and also the magnetic field component perpendicular to the simulation plane. The electric fields and the magnetic field are in the respective units of $m_e\omega_{pe}c/e$ and $m_e\omega_{pe}/e$.

laser produced plasma. Similarly to Ref. [11], the choice of density defines the temporal and spatial scales respectively as ω_{pe}^{-1} and c/ω_{pe}. The relation between the initial temperature T_0 and the ion flow velocity is an important parameter, which governs the plasma dynamics. In our case, the interaction starts with the two-stream instability ($v_0 > \sqrt{T_e/m_e}$), which precedes the Weibel instability development. Correspondingly, two types of shocks, electromagnetic and electrostatic, can be created [12].

It follows from the general structure of the quasilinear theory that the number of spatial dimensions can influence the diffusion coefficient, although it does not change the temporal evolution qualitatively [13]. Another aspect of dimensionality is the generation of turbulent fields. The filament merging could be different in 3D, thus leading to some differences in ion evolution. But the 3D effects of the filament interaction, as demonstrated in previous publications [2,14,15], appear at a substantially longer time scale than our simulation time, and they are not considered here.

Main question in understanding the collisionless shock formation is the electron heating mechanisms. While the initial electron heating occurs on the time scale of the order of a few tens of electron plasma periods, the shock formation time is much longer. It usually exceeds several tens of ion plasma periods because the rate of electron-ion energy exchange is limited by a large ion-to-electron mass ratio, $m_i/m_e = 1836$. Understanding the electron heating in the full-scaled simulation requires using a real mass ratio and a small time step. This is mandatory for development of a realistic physical model of a collisionless shock formation, but it requires great computational efforts.

At the very beginning of the interaction process, heating occurs at the front of the interacting plasmas. Fig. 2 shows the temporal evolution of the electron phase space. The fastest electron electrostatic two-stream instability develops near the plasma fronts (see panel A corresponding to the time of 50 τ_0). It heats the electrons in narrow front layers to a maximum energy that exceeds many times their initial kinetic energy. The electron distribution is strongly anisotropic because the heating proceeds only in the propagation direction. As the time passes, this heating mechanism remains localized at the fronts, but it may be able to perturb the ions at later times (see Fig. 4).

Another important process is the transverse electron heating in the interpenetration region (see panels B–D in Fig. 2 corresponding to the time steps 75, 100, and 125τ_0). As shown in panel D, the electron mean energy inside the overlapping zone even exceeds the energy at the fronts. This is a consequence of two processes: (i) mixing, isotropization of electrons coming from the oppositely propagating plasmas and (ii) stochastic electron heating in the turbulent fields. The two-stream instability develops at the plasma fronts in zones with a thickness of a few $v_0\tau_0$. The electrons coming from both plasmas mix, and their directional velocities are transformed in the chaotic parallel motion with the characteristic temperature of the order of the initial electron directional energy [7].

There are several later processes defining the energy redistribution between electrons, ions, and fields. Because the main free energy in the counterstreaming plasmas is stored in the kinetic energy of ions, it is important to explain how the ions are decelerated. Fig. 3 shows the energy balance obtained from the PIC simulation. The electromagnetic energy grows during the first 50 plasma periods. This corresponds to the excitation of the two-stream instability at the fronts. Furthermore, the electron energy starts to grow, and this corresponds to electron-ion energy exchange mediated by the electromagnetic fields.

As can be seen in Fig. 3, the electromagnetic energy remains much smaller than the particle kinetic energy. The explanation for this is that the fields are localized near the plasma fronts. Because the initial ion energy is in the mass ratio, $m_i/m_e = 1836$, which is