Electron heating and acceleration in two plasmas colliding with sub-relativistic velocities

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Abstract: Collisionless shock formation is investigated with large scale fully electromagnetic two-dimensional Particle-in-Cell (PIC) numerical simulations. Two plasmas are colliding in the center of mass reference frame at sub-relativistic velocities. Their interaction leads to collisionless stochastic electron heating, ion slowing down and formation of a shock front. We focus here on the initial stage of evolution where electron heating is due to the Weibel-like micro-instability driven by the high-speed ion flow. Filament generation, followed by turbulent mixing, constitute the dominant mechanism for energy repartition. The global properties are illustrated by examination of single filament evolution in terms of energy/particle density and fields.

1. Introduction

Collisionless shocks are quotidian events in the Universe. They transform energy of star explosions into hot plasmas, high energy particles and radiation. High-energy, hard X-ray flashes are therefore observed by satellite missions and ground-based stations. The origins and the mechanisms that generate collisionless shocks have been addressed recently with new large scale numerical simulations [1–3]. Laboratory experiments using plasma flows driven by high power, high energy laser systems are opening a new era in astrophysics and space science research. They will provide, for the first time, high energy plasma flows with sub-relativistic velocities that may give direct evidences of collisionless shock formation and evolution.

The mechanism for transfer of energy from fast ion flows to electrons and electromagnetic fields at a time scale much shorter than the time of electron-ion energy exchange in Coulomb collisions is related to plasma instabilities. Generation of strong electric and magnetic fields appear to slow down bulk flows and accelerate electrons and ions. However, the sequence of events leading to shock formation is not well understood. The process involves electron and ion anisotropic instabilities coupled to electron heating. The characteristic time of these processes seen in numerical simulations is very long, of the order of a hundred ion plasma periods or even more [1,3]. The complete process involves several subsequent steps that are not yet identified.

We report here on investigation of the initial stage of collisionless shock formation related to electron instabilities and electron heating by using the large scale PIC code PICLS [4]. The simulations are scalable from astrophysical conditions with the plasma densities of the order of a few particles per c.c. to the laboratory scale laser-produced plasmas with densities about 18–20 orders of magnitude higher. However, the plasma velocities are the same as well as the dominant physical processes. In high energy laser facilities the ion bunches can be accelerated to velocities greater than 1000 km/s in the ablation plumes. Moreover, in high power laser facilities the ion bunches with densities comparable to the solid density can be accelerated to energies of a few tens of MeV par nucleon, that is, to sub-relativistic velocities $\sim 0.1c$ via the process of Target Normal Sheath Acceleration [5]. By colliding two of these ion bunches or by interacting one of them with a gas plume one may create a sub-relativistic collisionless shock in the laboratory [6].

2. Large scale simulation of plasma inter-penetration

Our simulations are performed in the center-of-mass frame during the initial stage of evolution lasting of the order of ten ion plasma periods, $\omega_{pi}t \leq 60$, where ω_{pi} is the ion plasma frequency. During this time, the excitation of the Weibel instability results in electron and ion filamentation, strong electron heating, magnetic field generation and turbulent mixing. Hence, the dominant mechanisms for energy repartition between two counter-streaming plasmas are identified. These global properties are further illustrated by examination of single filament evolution in terms of energy/particle densities and fields.

At the initial time moment in the center-of-mass reference frame two plasmas of equal densities n_0 are facing each other at the interface $y_0 = 5024\ c/\omega_{pe}$ in the simulation plane (x,y), where ω_{pe} is the electron plasma frequency. The ratio of the electron to ion plasma frequency $\omega_{pe}/\omega_{pi} = 42.85$. The simulation box is 10048 c/ω_{pe} long and 80 c/ω_{pe} wide with the periodic boundary conditions in x-direction. There are 0.96 billion macro-particles in this simulation distributed over 0.8 billion cells. The overall simulation time 8400 ω_{pe}^{-1}. The bottom side plasma, $y < y_0$, has the streaming velocity $v_y = u_p = 0.2c$. The electrons have a temperature of 10 keV and the ions have a temperature of 100 eV. The top side plasma, $y > y_0$, have a streaming velocity $v_y = -u_p$ and both species, electrons and ions, have the same temperature of 100 eV. The difference in electron temperatures models the high speed ejecta (bottom plasma) and the cold target plasma (top plasma).

The electron energy density is the most important parameter characterizing the temporal evolution of colliding plasmas. Figure 1 shows the temporal evolution of the electron energy density in dimensionless units normalized by $n_0 m_e c^2$. As time progresses, filament structures are bending, breaking and then dispersing. Similar evolution can be seen while considering the filament evolution from the edges of the overlapping region to its center. Similar filamentary structures can be observed in the ion energy density distribution, electron and ion particle densities and the magnetic fields.

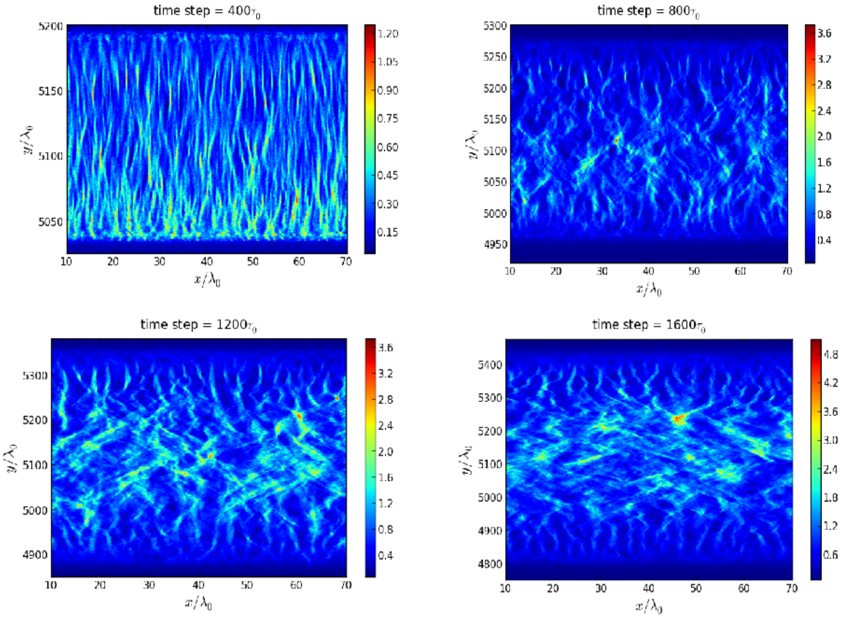

Fig. 1. Temporal evolution of ion energy density at the time $\omega_{pe}t$ = 400, 800, 1200 and 1600. The lengths are in the units of the electron skin depth c/ω_{pe}. The vertical scale of the figures changes as the time progresses.

The development of micro-instabilities leads to the mixing of electrons of both plasmas and heating them to the average energy that is much higher than the electron streaming energy $\varepsilon_e \sim m_e u_p^2 \sim 0.02\ m_e c^2$ (10 keV in our case). The distance between the filaments also evolves with time. At time 400 plasma periods, the peak to peak separation is about 2–3 c/ω_{pe}. At time 800 plasma periods, peak to peak separation remains the same at the edges of the overlapping zone. However, as one goes to the center, the peak to peak separation increases to 6–10 c/ω_{pe}. Filaments are merging: the increase in peak separation is evidence of mixing that occurs in plasma turbulence.

The nonuniform electric field and magnetic field structures that are created decelerate the streaming electrons and ions in the propagation direction, while slightly accelerating (heating) the warm plasma electrons and ions in the transverse direction. The source of the stochastic electron heating is the ion kinetic energy. The electrostatic field plays an important role in the electron heating. The detailed single filament analysis shows that the magnetic and electrostatic fields generated by the Weibel instability are random on the filament spatial scale. The Weibel instability causes the charged particle orbits to get smaller, forcing the filament structures to merge and break apart.

Our results show that equipartition of energy for non-relativistically colliding streams takes a long time. During the preliminary stages of plasmas inter-penetration, electron heating plays the dominant role. The electron energy increases up to a factor of 10 and then levels off as the instability saturates. These conclusions follow from analysis of the fields, energy density and particle density distributions. At instability saturation, a significant part of the ion streaming energy is transferred to the magnetic field and the electron thermal energy.

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