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The formation of a relativistic planar plasma shock

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Abstract

The shock is considered that develops, when two plasma clouds collide at the speed 0.9 c. Initially, an almost flow-aligned magnetic field is introduced, which decreases the growth rates of the oblique mixed mode instability and of the filamentation instability. A 2D PIC simulation demonstrates that a planar, electromagnetic wave structure is growing that amplifies the magnetic field component orthogonal to the flow velocity vector. The formation of the forward and reverse shocks is followed with a 1D PIC simulation and it is shown that an energy equi-partition is established downstream between the ions, the electrons and the magnetic field.

Introduction

A plasma collision at a mildly relativistic speed is modelled by PIC simulations in one and in two spatial dimensions, taking an ion-to-electron mass ratio of 400 and a temperature of 100 keV. This high temperature may be representative for a gamma-ray burst (GRB) jet [1]. The energy of an initial quasi-parallel magnetic field is one percent of the plasma kinetic energy, which suppresses the filamentation- and the mixed mode instability [2]. The initial magnetic energy is probably low enough to be conform with the fireball model of GRBs. The weak component of the magnetic field that is perpendicular to the flow velocity vector allows the development of waves other than the electrostatic ones [3]. The dissipation of energy by a growing wave pulse of mixed polarity, probably an oblique whistler wave, and different densities of the colliding plasma clouds [4] result in a shock forming during milliseconds. The shock, which develops for a collision speed of 0.9 c, accelerates electrons to the Lorentz factor $\Gamma \approx m_i/m_e$. Such a strong electron acceleration by oblique shocks has also been observed elsewhere [5]. A downstream region forms, in which the plasma approaches an energy equi-partition between electrons, ions and the magnetic field [6]. The electron energy spectrum resembles a power-law at high energies with N(E) $\propto E^{-2.7}$. The magnetic field at the shock, which is quasi-perpendicular due to its shock amplification, reflects upstream ions. They form a beam that can drive further instabilities in the foreshock. The forward and the reverse shocks are asymmetric due to the unequal cloud densities. The forward shock may be representative for the internal GRB shocks.

Simulation results

We verify, if the flow-aligned magnetic field component suppresses the filamentation. A 2D PIC simulation models the plane spanned by the flow velocity vector (x-axis) and one orthogonal direction, here the y-direction. We follow the plasma collision to the time $t = 200$ in units of the inverse box-averaged plasma frequency Ω_p^{-1}, where $\Omega_p = (\omega_{p1}^2 + \omega_{p2}^2)^{1/2}$ with ω_{p1}, ω_{p2} being the electron plasma frequencies of the dense and tenuous beam, respectively, and $\omega_{p1} = \sqrt{10}\omega_{p2}$. The flow aligned magnetic field $B_{0,x} = (m_e/e)\omega_{p1}$ with e, m_e being the elementary charge and electron mass. We set $B_{0,z} = B_{0,x}/10$. More information is detailed in Ref. [6]. Figure 1 shows the B_z-components close to the front of the dense cloud at $x - x_0 \approx 120$ at the simulation's end. Positions are in units c/Ω_p and x_0 is the initial contact position of both clouds. Figure 1(a) shows a planar structure.

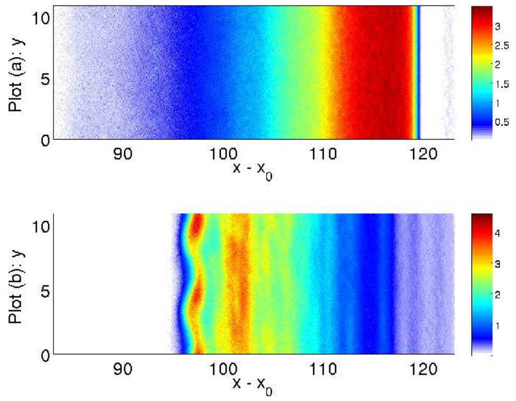

Figure 1: The magnetic power $P_z(x,y) = c^2(B_z[x,y] - B_{z,0})^2$ at $t \approx 200$ and in $10^6 V^2/m^2$. (a) corresponds to a simulation with a parallel B-field and (b) to one without. (a) shows a planar structure.

The 1D simulation, which exploits this planarity and removes the y-direction, expands the spatio-temporal range accessible to the PIC simulation to $t = 5260$. The beams of ions with $m_i = 400 m_e$ with their initial relative flow speed $0.9c$ are strongly modulated at $t = 1500$ in Fig. 2. They have practically merged along the p_x−direction, which evidences the onset of a shock. Their corkscrew orbits are caused by the now strong perpendicular magnetic field component, which belongs to a circularly polarised mainly electromagnetic wave packet. The amplitude of this wave packet is still growing [6]. The ion modulation increases further and for $t = 5260$ a downstream region has formed in the interval $1800 < x - x_0 < 2000$, which separates a forward shock from a reverse shock.

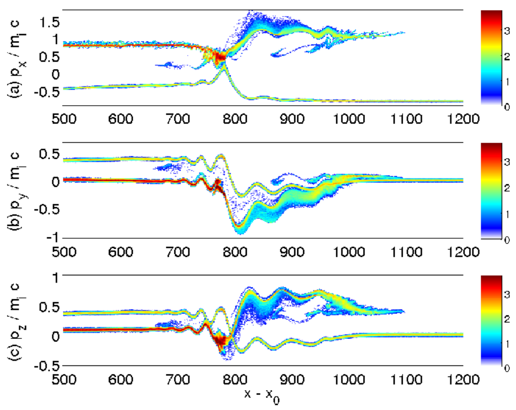

Figure 2: The ion distribution at $t = 1500$, projected onto the (x, p_x)-plane (a), the (x, p_y)-plane (b) and the (x, p_z)-plane (c). The color is the 10-logarithm of the number of computational ions of cloud 1.

This is demonstrated by the Fig. 3. The downstream region is moving at the speed $0.3c$, because of the conservation of momentum and the different cloud densities. The forward shock moving to increasing x is thus the faster one. A shock-reflected ion beam is visible for $x - x_0 > 2500$, which is a well-known signature of nonrelativistic shocks [4]. The electrons can reach $\Gamma \approx m_i/m_e$ in the downstream reference frame [6], suggesting an energy equi-partition with the ions.

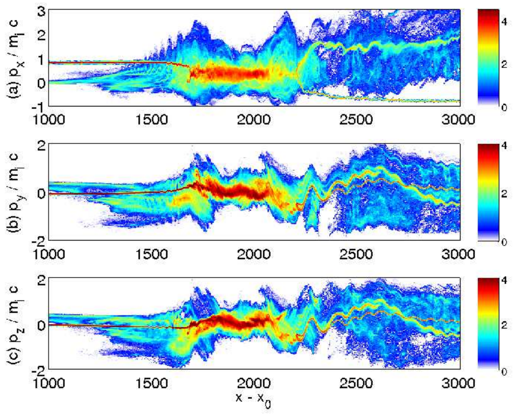

Figure 3: The ion distribution at $t = 5260$, projected onto the (x, p_x)-plane (a), the (x, p_y)-plane (b) and the (x, p_z)-plane (c). The color is the 10-logarithm of the number of computational ions of cloud 1.

The energy distributions of the electrons and ions are compared. At $t = 5260$ the electrons have thermalized in the downstream and we may assume a gyrotropic distribution. The downstream magnetic field is almost perpendicular to the x-direction.

The electron distribution as a function of $\Gamma_x = (1 - v_x^2/c^2)^{-1/2} - 1$ can thus serve as an indicator for the peak energy the electrons reach and we compare it to the ions' equivalent. The distributions are integrated over the interval $1800 < x - x_0 < 2000$ in Fig. 3. We introduce the scaling factor $C_N = 1$ for the electrons and $C_N = m_i/m_e$ for the ions. The flow aligned energy distribution is displayed in Fig. 4(a). The peak energy of both species is in good agreement and the distribution is qualitatively in agreement. We conclude that both species are approximately in an equilibrium. Note that a full equilibrium is probably not established, because the ion distribution in the downstream region in Fig. 3 shows some non-thermal components.

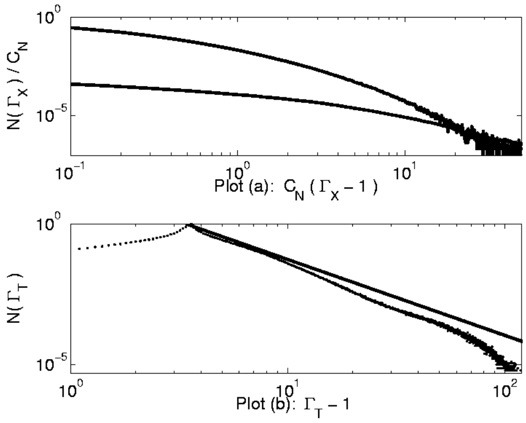

Figure 4: Downstream energy distributions at $t = 5260$: (a) shows the electron- (upper curve) and ion distributions $N(E_p)$ with $E_p = C_N(\Gamma_X - 1)$ and $\Gamma_x = (1 - v_x^2/c^2)^{-1/2}$. (b) shows the electron distribution $N(E_T)$ with $E_T = (1 - \mathbf{v}^2/c^2)^{-1/2} - 1$ and $N(E_T) \propto E_T^{-2.7}$.

The electron energy spectrum integrated over the same interval and as a function of the total kinetic energy is plotted in Fig. 4(b). The electron distribution at high energies up to $\Gamma_T \approx 80$ follows approximately a power-law with an index slightly below -2.7.

Summary

The collision of two plasma clouds with a speed of 0.9 c has been examined with PIC simulations. The cloud density ratio has been 10 to facilitate the formation of a fast shock [4]. A practically flow aligned magnetic field has suppressed [6] the filamentation instability during the time interval covered by the 2D PIC simulation. We have exploited this planarity to resort to a 1D PIC simulation, which could resolve electron and ion scales at a high ion-to-electron mass ratio. We have to emphasize though that the planarity of the system may not persist until the formation of the shock. However, by decreasing the flow speed and by increasing the magnetic field somewhat, a planarity can eventually be enforced [2].

The 1D PIC simulation demonstrated the growth of a circularly polarized wave packet with an amplitude, which is sufficiently high to reflect and to thermalize the ion beams. An approximate energy equipartition between the electron, the ion and the magnetic energy densities has been observed in Ref. [6]. The extreme electron acceleration is in line with previous studies of interactions between a short plasma cloud and a background plasma [5].

The rapid development time of the shock, the extreme electron acceleration and the powerful magnetic fields at the still mildly relativistic flow speed make shocks of this type suitable mechanisms for the generation of the prompt emissions of gamma-ray-bursts [6].

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