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Plasma collisions at mildly relativistic speeds: Formation of an electrostatic turbulent boundary layer

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Abstract

Plasmas collide at relativistic speeds in many astrophysical and high energy density laboratory environments [1, 2]. The collision boundaries are not well understood. In the absence of a magnetic field $\mathbf{B}_0$ that is parallel to the flow velocity vector $\mathbf{v}_b$ the boundaries are filamentary, since waves grow with wavevectors $\mathbf{k}$ that are not parallel to $\mathbf{v}_b$. Modelling such boundaries requires large 3D particle-in-cell (PIC) simulations [3]. A flow-aligned $\mathbf{B}_0$ can suppress wave modes other than $\mathbf{k} \parallel \mathbf{v}_b$ [4], as multi-dimensional PIC simulations show [5, 6]. We select a $\mathbf{v}_b$, a plasma temperature T and $\mathbf{B}_0$, for which the growth rate of the two-stream instability exceeds that of all other instabilities. We exploit this planarity to resort to a 1D simulation, that lets two identical electron-proton plasma slabs collide with a relativistic speed and a Mach number of over 400. The developing electrostatic turbulent boundary dissipates its energy via electron phase space holes that accelerate electrons to relativistic speeds and increase significantly the speed of some protons. The results are important in the context of a dynamic accretion disc and microquasar jets. The accelerated electrons may feed the disc wind and the relativistic leptonic jets, and possibly contribute to the hard radiation component of the accretion disc.

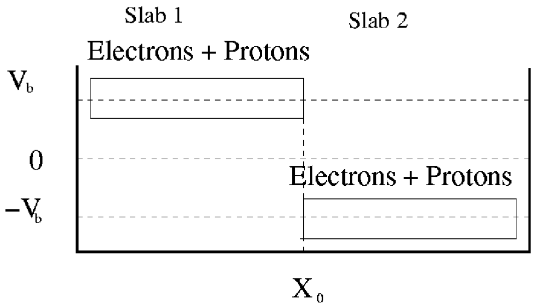

Figure 1: The initial conditions: Two $e^- p^+$plasma slabs that move along x in opposite directions collide at the position X_0. Both slabs have the same temperature, composition and density.

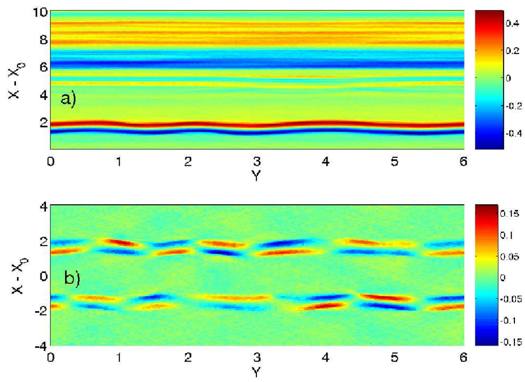

Figure 2: The electric fields at $t\,\omega_p = 59$ in the 2D simulation in units of $c m_e \omega_p / e$. Panel (a) shows the electrostatic E_x component and panel (b) the electromagnetic E_y component.

Particle in cell (PIC) simulation

PIC codes solve the Maxwell equations for the electromagnetic fields $\mathbf{E},\mathbf{B}$, which are defined on a grid. The plasma is represented by an ensemble of phase space volume elements (computational particles) that follow continuous trajectories. We employ the full mass-ratio $m_p = 1836\,m_e$. The computational particles (CPs) are evolved in time with the Lorentz equation. The time-evolution equations are

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t}, \quad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (2)$$

$$\frac{d\mathbf{p}_i}{dt} = q_c \left(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}\right), \quad \frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i. \quad (3)$$

The particles and fields interact through the current $\mathbf{J}$. The initial plasma setup is depicted in Fig. 1. We initialize the simulation such that $\mathbf{E} = 0$ and $B_{0y} = B_{0z} = 0$. The electron plasma frequency of each slab is $\omega_p = (e^2 n_e / m_e \varepsilon_0)^{1/2}$ and $\omega_c = eB_{0x}/m_e = \omega_p$. We set $v_b = 0.18\,c$ and $\mathbf{v}_b = v_b\,\mathbf{e}_x$. We do a 2D simulation in the $x-y$ plane with the box width $L_y = 6\,c/\omega_p$ along y and a 1D simulation aligned with x. More details are listed in Ref. [6].

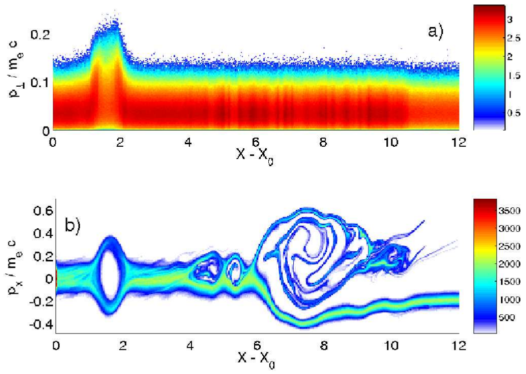

Figure 3: The electrons at the time $t\,\omega_p = 59$ in the 1D simulation. (a) shows electrons that accelerate orthogonally to $\mathbf{e}_x$ at $x - x_0 \approx 1.6$. (b) illustrates that these electrons form a well-defined electron phase space hole. The phase space hole at $x - x_0 \approx 8$ remains electrostatic.

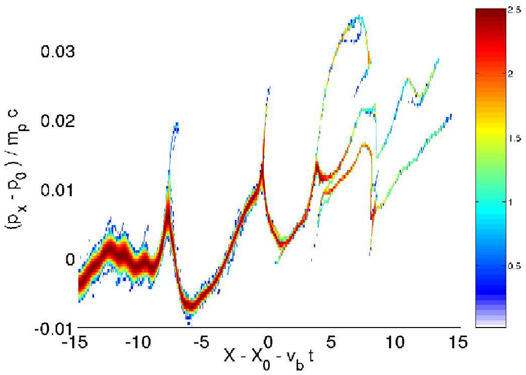

Figure 4: The protons at $t\,\omega_p = 59$ in the 1D simulation. The charge layer due to the leading electron phase space hole modulates and accelerates protons.

Results

The colliding slabs will trigger streaming instabilities. The flow-aligned $\mathbf{B}_0$ should suppress all but the electrostatic two-stream instability, which triggers waves with $\mathbf{k} \parallel \mathbf{v}_b$ [4]. Mixed and filamentation modes result in other orientations of $\mathbf{k}$ relative to $\mathbf{v}_b$. Figure 2 demonstrates that purely electrostatic structures develop and a bipolar one, which is partially electromagnetic.

The partially electromagnetic field structure at $x - x_0 = 1.6$ is quasi-planar and $E_x \approx 3E_y$. The underlying electron dynamics should thus be represented also by the 1D simulation. We examine the electron phase space distribution in the 1D simulation at $t\,\omega_p = 59$. E_y is driven by an electron flow perpendicular to $\mathbf{e}_x$. The smooth phase space hole arising from our choice of the initial conditions [6] is unstable to electromagnetic instabilities, whereas the turbulent hole at the leading edge has not developed any E_y component.

The protons at the leading edge of the slab are accelerated by the time-dependent E_x potential. At the simulation's end $t\,\omega_p = 1200$ (not shown) the protons have been accelerated by about 20%.

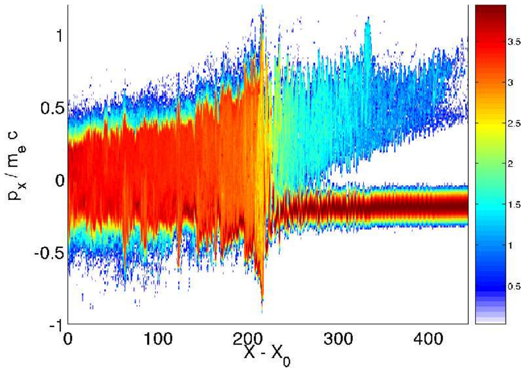

Figure 5: The electrons at $t\,\omega_p = 1200$ in the 1D simulation. A turbulent layer has formed, separating the downstream electrons from the cool upstream electrons and the beam of shock-reflected electrons.

At $t\,\omega_p = 1200$ a turbulent boundary layer has developed that separates downstream electrons from cool upstream electrons and a beam of reflected electrons. The downstream and beam electrons are riddled with phase space holes [6].

Summary

We confirm that a flow-aligned magnetic field can suppress the growth of mixed/filamentation modes during the initial plasma evolution, if two equally dense plasma slabs collide. Some electron holes are, however, unstable to an electromagnetic instability that can overcome the magnetic field. No shock involving protons has developed. The beam of reflected electrons has, however, been accelerated to a mildly relativistic speed. The collision speed of the slabs is that of shocks in the accretion discs of microquasars [7]. The upstream electron temperature is representative for the blackbody temperature of the accretion discs and the downstream electrons may feed the non-thermal disc emissions [8].

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References

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