Magnetic field amplification and electron acceleration to near-energy equipartition by a mildly relativistic quasi-parallel plasma protoshock.

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Introduction

Mildly relativistic shocks appear in many astrophysical and laboratory contexts, showing a rich variety of physical properties. As the shocks form, they liberate considerable quantities of kinetic energy, which can variously be converted into thermal energy, stored as magnetic field energy and used to accelerate a small population of electrons and ion to relativistic speeds. Gamma ray bursts (GRBs) are extraordinarily powerful flashes of electromagnetic radiation, the most luminous in the universe. The fireball model for gamma ray bursts [1] proposes an ultrarelativistic jet launched from the collapse of a star to form a compact object, as the source for GRBs. The intense GRB radiation is observed to have short variability timescales $\Delta T/T \sim 10^{-2}$. The short variability timescale is consistent with multiple internal shocks along the jet beam [2]. While much has been discovered about GRBs, the emission mechanism which creates the bursts is not yet understood. Highly polarized emission suggests the presence of an ordered magnetic field in the emission region [3]. We seek to find, using numerical simulations, configurations of mildly relativistic shocks with strong background fields which can accelerate electrons to ultrarelativistic speeds, and simultaneous amplify the jet's magnetic field to large values, consistent with observed gamma radiation.

Numerical method and initial conditions

Previous studies have focused on colliding plasma shells with equal densities. Relaxing the assumption of a uniform density changes the linear dispersion relation. In order to model the physics of a mildly relativistic shock, where particles interact through the medium of the electric and magnetic fields, we use the Particle-In-Cell (PIC) method [4]. Maxwell's equations and the Lorentz-Newton equation are solved in 2D.

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}, \nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J}, \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0, \nabla \cdot \mathbf{E} = \rho, \tag{2}$$

$$d_t \mathbf{p}_j = q_j \left(\mathbf{E} + \mathbf{v}_j \times \mathbf{B}\right), \mathbf{p}_j = m_j \Gamma \mathbf{v}_j, d_t \mathbf{x}_j = \mathbf{v}_j. \tag{3}$$

Our initial conditions are as follows: The inclination angle relative to the flow velocity vector of the initial magnetic field $\mathbf{B}_0$ is 0.1 radians and its magnitude $|\mathbf{B}_0| = R^{1/2}$ in our normalization, where $R = m_i/m_e = 250$ is the reduced ion/electron mass ratio. The beam velocity is $v_b = 0.63c$ giving a collision speed of $v_s = 2v_b/(1+v_b^2) = 0.9c$. This speed jump will be distributed over the forward and reverse shocks. The temperature of all species is $T = 131$keV. The thermal velocity of the electrons is $v_{th,e} = \sqrt{kT/m_e} = 0.83v_b = 0.52c$. The thermal velocity is chosen to be comparable the collision speed, as expected for internal shocks in GRB jets. The thermal velocity of the ions is $v_{th,i} = v_{th,e}/\sqrt{R} = 0.033c$. The initial density ratio is chosen to be 10.

Results

The electric and magnetic fields are first to react to the plasma collision. The initial configuration of a collision in a quasi-parallel field means that there is a sign change in the convective electric field across the collision boundary. This results in a rapid growth in the magnetic field. This growing magnetic field in turn deflects both charged species.

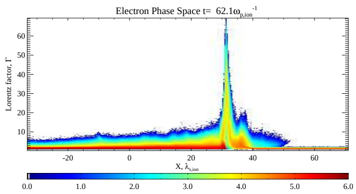

Figure 1: Electron (Γ, x) phase space at $t = T_1$

Electrons, having shorter timescales than the more massive ions, feel the effects of the plasma collision more rapidly and are accelerated at the collision boundary. At $t \sim 60\omega_p^{-1}$ the fastest electrons have reached Lorentz factor > 50 (Figure 1). The electrons which are accelerated are confined to a small region in x-space. This implies their acceleration takes place primarily orthogonal to the x-axis. The amplification of the magnetic field due to the jump in convective electric has an important effect on the geometry, maintaining a planar front.

The flow of electrons along the shock boundary increases the current, thus increasing the induced magnetic field. Striations created as ions begin counterstreaming compete with this effect. The parallel counterstreaming current elements bunch together, while antiparallel elements repel each other. The resultant mergers create arrays of filaments in the simulation. Both the ion and the electron clouds show signs of filamentation, however the electrons are much more diffused than the ions so the filaments are less distinct. Eventually the field becomes strong enough to deflect ions (as shown in Figure 2). No clear reverse shock is seen forming at the time. The process saturates when the filaments have reached size scales of 0.1 ion skin depths.

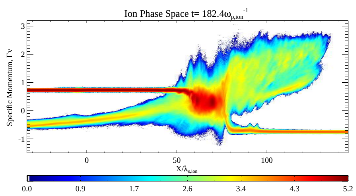

Figure 2: Collision of plasma clouds: ion $p_x - x$ phase space

As the simulation continues the magnetic field is rotated from a quasi-parallel to a quasi-perpendicular sense, strongly enough to deflect ions back into the region upstream of the dense cloud. This causes the distribution of the particles to change, as electron entering the region of enhanced magnetic field intensity are reflected more rapidly than ions, due to shorter gyroradii. The charge separation generates an electric field component parallel to the flow, which drags the electrons across the perpendicular magnetic field, accelerating them along the cloud front. Electron acceleration amplifies the current, the current amplifies the magnetic field and provides feedback into the acceleration of electrons. The process cuts off when electron inertia becomes comparable to the ions. Populations of both electrons and ions are deflected at the collision boundary. Kinetic energy is converted into thermal energy behind the collision boundary leading to the formation of a hot downstream region, which can be fitted with a Maxwell-Jüttner distribution with $v = 0.33c$.

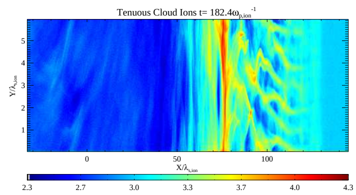

Figure 3: Ion filamentation at $t = T_{end}$

Figure 2 shows the two colliding ion beams. In the upstream of the forward shock ($X > 75$) a broad region of ions with specific momentae $p_x > 1$ can be seen. This is a combination of reflected ions from the right beam and modulated ions from the left beam. This ion distribution results in a thermal anisotropy and, consequently, it is in this region where the clearest signs of the filamentation can be seen(Figure 3).

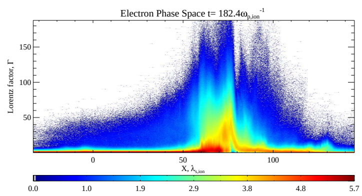

Figure 4: Electron (Γ, x) phase space at $t = T_{end}$

At the end of the simulation a tenuous population of electrons has reached near energy equipartition with ions (Figure 4) . This can be compared with the results in 1D of [5], whose results also scale to energy equipartition.

More insight into the processes at work in the plasma can be gained from investigating the currents flowing. Current filaments are deflected at the collision boundary by the strong quasi-perpendicular magnetic field. The filaments are seen to rotate into vortices in plots of both perpendicular and poloidal current (Figure 5). The filamentary morphology is replaced by an elliptical structure. The J_z current increases towards the centre of the vortex, while the poloidal current is at its greatest in the edge of the structure. The vortex structure increases steadily in size throughout the simulation until it fills the simulation box.

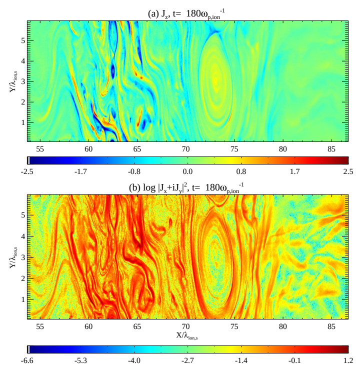

Figure 5: Current vortex formation: J_z and $\log\left|J_y^2 + J_z^2\right|$ and

The structure is elliptical - its minor axis is compressed in the direction of flow - partially due to relativistic length contraction. The final structure is resembles a flux tube. The flux tube stores both accelerated electrons and magnetic field.

Summary

In this work we have performed a simulation of a plasma collision along a quasi-parallel magnetic field. The density ratio is 10. The aim was to understand and probe the mechanisms whereby electrons are accelerated and magnetic field is amplified.

Our main conclusion is quasi-parallel plasma collisions can accelerate electrons to near energy-equipartition with ions. We also find that the magnetic field is strongly amplified. Finally we find that a stable vortex structure is found for magnetic field generated in vortices. Such current vortices may scale up to MHD size scales.

We find evidence of a feedback process, initiated by the growth of the magnetic field. This field, in combination with an electric field component generated by charged separation of ions and electrons, triggers an accelerated electron current, which amplifies the field. The process continues until the electrons are near ion energies, at which point they can no longer be accelerated.

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