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Electron acceleration by a relativistic twostream instability with oblique B

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Abstract

Electrons that are trapped by a quasi-electrostatic wave move, on average, with the phase speed of the wave. In the presence of a magnetic field **B**, the trapped electrons could, in principle, be accelerated to cosmic ray energies through cross-field transport. We model this cross-field transport with a particle-in-cell (PIC) simulation for an oblique **B**. The electron energies at the simulation's end exceed 5 MeV for all pitch angles and they can reach GeV energies along the wavevector. We discuss environments, in which such conditions may exist and for which such an acceleration would be relevant.

Introduction

The radiation and the relativistic plasma jets observed at some astrophysical sources, like active galactic nuclei (AGNs) and gamma ray bursts (GRBs) [1], imply the existence of efficient particle acceleration mechanisms, e.g. the cross-field transport of electrons, which are trapped by a fast quasi-electrostatic wave. Quasi-electrostatic waves with a high phase speed can be produced by a two-stream instability. If their wavevector $\mathbf{k}_u$ is perpendicular to the ambient **B**, we get electron surfing acceleration [2] (ESA), which can accelerate electrons up to a Lorentz factor that equals the proton-to-electron mass ratio $m_p/m_e = 1836$ [3]. These electrons move perpendicularly to **B** and they could contribute to the radio emissions of AGNs through their synchrotron emissions. ESA can, however, not contribute to relativistic plasma flow, i.e. jets, since the electron speed along **B** is unchanged. Here, we rotate **B** with respect to $\mathbf{k}_u$, to allow for a field-aligned electron acceleration. We show that this gives rise to relativistic electron speeds

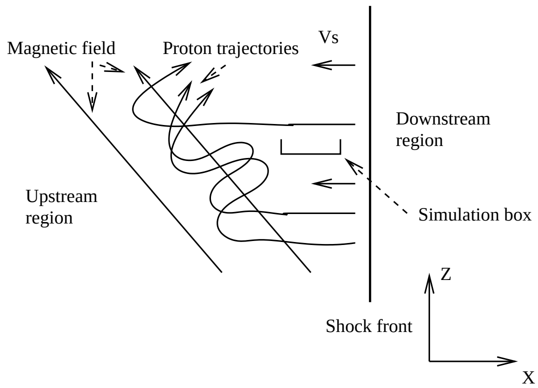

Figure 1: The foreshock: The shock expands into the upstream region. It reflects ions (protons). The shock-reflected proton beam moves through the upstream (electron-proton) plasma. On the small scale covered by our simulation box, the beam is spatially homogeneous.

parallel and perpendicular to **B** [4, 5].

Simulation / initial conditions

PIC codes [6] solve the Maxwell equations and the relativistic Lorentz equation of motion:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t}, \tag{1}$$

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

$$\frac{d\mathbf{p}_i}{dt} = q\left(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}\right). \tag{3}$$

Each computational particle with the index i is followed through phase space. The particles and fields are connected through the current $\mathbf{j}$.

A shock, which moves at the speed $0.9c$ and reflects the upstream ions specularly [7], results in protons that move with the speed $v_b \approx 0.99c$ in the upstream frame, as sketched in Fig. 1. This proton beam will give rise to a two-stream instability and the growing quasi-electrostatic waves have phase speeds comparable to the beam speed, i.e. the wave moves at relativistic phase speeds.

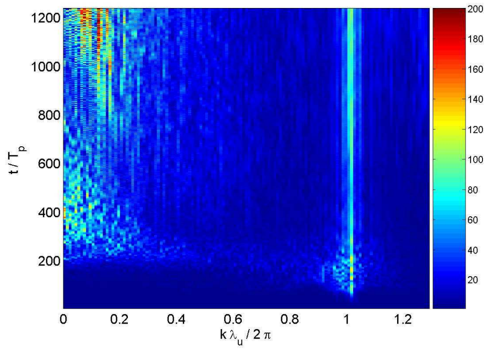

Figure 2: The time evolution of the spatial amplitude spectrum of the electrostatic field in units of V/m: The wave in the simulation grows at the wavenumber $k \approx k_u$. It maintains this k after its saturation and the amplitude is constant. The electric fields with $k \ll k_u$ indicate the onset of a secondary instability [9]

The electron number density, the background and the beam proton number density are n_e, n_p and n_b, respectively, and $n_p = n_e$, $n_b = n_e/2$. The temperature of the upstream plasma is 100 eV and that of the proton beam is 26 keV. The number density and the temperatures are spatially homogeneous. They define the characteristic time and frequency in the simulation:

Plasma frequency	$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$	$10^5 \frac{2\pi}{s}$
Electron gyrofrequency	$\omega_c = \frac{eB_0}{m_e}$	$\omega_p/70$
Plasma period	$T_p = \frac{2\pi}{\omega_p}$	$10\,\mu s$

We resolve the x-direction and all three components of $\mathbf{p} = \mathbf{v}/\sqrt{(1-v^2/c^2)}$. The box is aligned with the x-direction and **B** is tilted by 45°, as shown in Fig. 1 and discussed in Ref. [5]. The plasma temperature is low and $\omega_c \ll \omega_p$, which results in a two-stream instability [8]. It leads to wave growth at the wavenumber $k_u = \omega_p/v_b$ and the frequency $\omega_u \approx \omega_p$.

The wave saturates by electron trapping [5] and these electrons are transported by the saturated wave with the phase speed $v_{ph} = \omega_u / k_u \approx v_b$ across **B**. The wave is stable, as demonstrated by the Fig. 2. The electrons are accelerated by their nonlinear interactions with the quasi-electrostatic wave and **B**; the trapped electrons undergo a continous acceleration similar to ESA and some others interact stochastically with the fields [4]. The electron phase space distribution in the Fig. 3 reveals ultrarelativistic phase space structures.

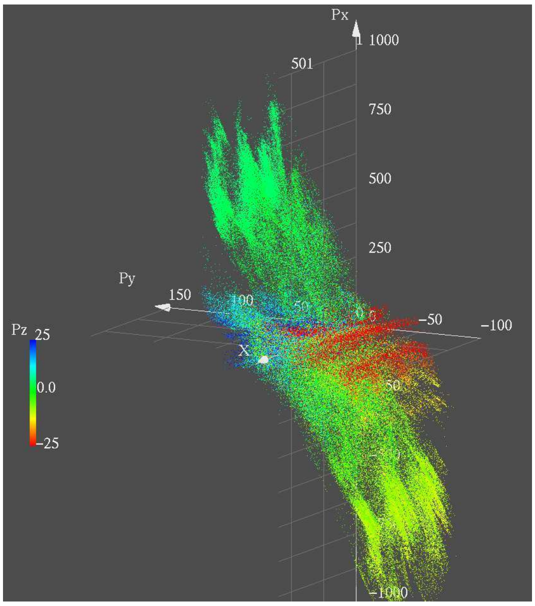

Figure 3: The electron phase space distribution in a simulation box subinterval at $t = 1270T_p$: Electrons are predominantly accelerated in the x-direction but also reach relativistic p_y and p_z.

The electrons show ultrarelativistic momenta in all momentum directions. This is a contrast to ESA, which would accelerate the electrons only in the x, y directions [2, 3]. The spatially integrated electron momentum distribution in the Fig. 4 shows statistically significant electron numbers at all pitch angles relative to **B**.

Summary

The cross-field transport of trapped electrons across **B** and the stochastic interaction between electrons and the electromagnetic fields can accelerate them to peak gamma factors comparable to m_p/m_e, the proton to electron mass ratio. It appears as if this is the upper limit for the fastest electrons that have been accelerated by their cross-field transport or by their stochastic interaction with the waves, at least in what the acceleration of the bulk electrons is concerned. Once the relativistic electron mass reaches the nonrelativistic proton mass, the plasma has lost the mobile species and the plasma dispersive properties must change.

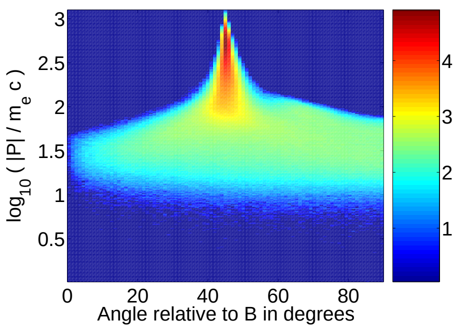

Figure 4: The electron momentum / pitch-angle distribution: The most energetic (trapped) electrons move in the direction of the wave. Less energetic (stochastically accelerated) electrons move in all other directions.

The relativistic electron speed orthogonal to the magnetic field implies that they can emit synchrotron radiation [3].

In this work we have examined the possibilities, which the cross-field transport and the stochastic interaction offers for the acceleration of electrons along the magnetic field. We have demonstrated that, if the magnetic field is oriented obliquely to the wavenumber of the quasi-electrostatic wave, the field-aligned electric field component can accelerate the electrons to gamma factors of the order of 10 – 100 along **B** without a reduction of the overall accessible gamma factor. These electrons can leave the acceleration region and emerge, for example, from an accretion disc in form of a wind. The electrons may also form components of relativistic jets.

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