Advances in Plasma Astrophysics
Proceedings IAU Symposium No. 274, 2010
A. Bonanno, E. de Gouveia Dal Pino & A. G. Kosovichev, eds.

doi:10.1017/S1743921311007472

Formation of electron clouds during particle acceleration in a 3D current sheet

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Abstract. Acceleration of protons and electrons in a reconnecting current sheet (RCS) is investigated with the test particle and particle-in-cell (PIC) approaches in the 3D magnetic configuration including the guiding field. PIC simulations confirm a spatial separation of electrons and protons towards the midplane and reveal that this separation occur as long as protons are getting accelerated. During this time electrons are ejected into their semispace of the current sheet moving away from the midplane to distances up to a factor of $10^3 - 10^4$ of the RCS thickness and returning back to the RCS. This process of electron circulation around the current sheet midplane creates a cloud of high energy electrons around the current sheet which exists as long as protons are accelerated. Only after protons gain sufficient energy to break from the magnetic field of the RCS, they are ejected to the opposite semispace dragging accelerated electrons with them. These clouds can be the reason of hard X-ray emission in coronal sources observed by RHESSI.

Keywords. Sun: flares, plasmas, acceleration of particles, magnetic field

1. Introduction

Simulations of particle trajectories by using a test particle approach in a 3D magnetic configuration with the guiding field emulating a simple case of magnetic reconnection were carried for a constant reconnection electric field (Zharkova & Gordovskyy, 2004) or for those enhanced near the X-nullpoint due to anomalous resistivity (Wood & Neukirch, 2005). Zharkova & Gorodovskyy (2004) showed that the trajectories of particles with the opposite charges (electrons or protons) can be either fully symmetric or strongly asymmetric towards the midplane of the RCS depending on the ratio between the magnetic field components.

As a result, some fraction of the released magnetic energy is transformed into kinetic energy of accelerated particles. The energy spectra of these particles also depend on a magnetic field topology, electric field strength and the dependence of transverse magnetic field on a distance from the X-nullpoint. Accelerated particles gain energies up to 100 keV for the electrons and up to 1 MeV for the protons (Zharkova & Gordovskyy, 2005a; Wood & Neukirch, 2005; Zharkova & Agapitov, 2009). Spectral indices of energy spectra gained at acceleration vary from 2 for electrons and 1.5 for protons if the transverse magnetic field linearly increases with the distance. Spectral indices for both electrons and protons become much higher if the transverse magnetic field increases exponentially with a distance from the X-nullpoint (Zharkova & Gordovskyy, 2005b).

More realistic approach considering plasma feedback to accelerated particles is archived with PIC simulation allowing to reproduce electro-magnetic fields generated by accelerated particles (Birn *et al.*, 2001; Tsiklauri & Haruki, 2007; Siversky & Zharkova, 2009) for reduced proton-to-mass ratios. These studies reproduced well magnetic reconnection rates (Birn *et al.*, 2001) and some key features of accelerated particles; power law energy spectrum and energy gains up to 100 keV.

Recent study of 3D magnetic reconnection with PIC by Drake *et al.* (2006) carried out for reduced proton skin depths related to a reduced magnitude for the speed of light, $c = 20V_A \approx 6 \cdot 10^6$ m/s, where V_A is the Alfvén velocity, revealed formation of two magnetic islands with X null points from both sides caused by tearing mode instability. Particles (electrons) then are supposed to be accelerated in stochastic second order Fermi acceleration by moving between these magnetic islands; although this mechanism does not seem to work for protons. This approach used a reduce simulation region size by reducing the skin depths for electron and protons, making all the reconnection features rather microscopic while in real flare events the current sheet thickness can achieve thousands km see, for example,]sui03.

2. Description of models

In this paper we apply iterations of test particle and PIC approaches for the simulation of particle acceleration in a 3D reconnecting current sheet with simple magnetic field topology. We assume that the current sheet plasma has typical coronal density of 10^{16} m^{-3}, which is in equilibrium with the background magnetic field. However, in order to avoid the problem with the small Debye length in the PIC approach, only a small fraction of the plasma particles (with density of 10^{10} m^{-3}) is included in the PIC simulation. This makes the ratio δ_i/λ_D to be of the order of 10. Electric and magnetic fields generated by particles in the PIC technic were then used in TP approach in order to investigate particle trajectories and densities.

Magnetic field topology

Since the electron or proton acceleration time is much shorter than the time of a reconnecting magnetic field variation as shown by Priest & Forbes (2000), one can assume the background magnetic field to be stationary. Also, from the TP simulations one finds that travel distances of accelerating particles along the RCS are of the order of 10 km at most (for the protons) (Zharkova & Agapitov, 2009) and this length is much shorter than the length scale of magnetic field variations along the current sheet. In addition, we assume that the magnetic field variations across the current sheet have much shorter length scale than along the current sheet, i.e. $L_x \ll L_z, L_y$.

The simulation domain is a small part of the RCS (see model in Siversky & Zharkova, 2009), but still large enough to contain the full trajectories of accelerated particles. The main component B_z depends on x as follows: $B_z(x) = -B_{z0} \tanh\left(\frac{x}{L_x}\right)$. Similar to Zharkova & Gordovskyy, 2004, the B_x component is assumed to be constant inside the simulation domain, i.e. $B_x = -B_{x0}$. The guiding (out-of-plane) magnetic field B_y is maximal in the midplane and vanishes outside the RCS: $B_y(x) = B_{y0}\text{sech}\left(\frac{x}{L_x}\right)$. Contrary to the TP simulations, plasma particles in the PIC simulations are considered to generate their own electric and magnetic fields, which is now self-consistently taken into account as described by Siversky & Zharkova (2009).

Reconnection electric field

In order to provide the inflow of plasma in our simulation domain we set up a background electric field, as those drifted in with velocity V_{in} by a magnetic diffusion process as shown by Priest & Forbes (2000): $E_{y0} = V_{in} \times B_{z0} + \frac{1}{\sigma\mu}\frac{\partial B_z}{\partial x}$, where V_{in} is the inflow velocity, σ is the ambient plasma conductivity, μ is magnetic permeability. On the boundaries of an RCS we ignore the gradient of the magnetic component B_z over x-coordinate by putting the second term to zero.

Simulations are carried out for the following current sheet parameters: the main component of the magnetic field $B_{z0} = 10^{-3}$ T, the current sheet half-thickness $L_x = 1$ m, the drifted electric field $E_{y0} = 250$ V/m and the guiding, B_{y0}, and transverse, B_{x0}, components of the magnetic field are selected to range from $(0.1 - 10) \times 10^{-4}$ T to cover acceleration at the various parts of RCS.

3. Results

The PIC simulations shown that the induced magnetic field $\tilde{\mathbf{B}}$ is much smaller than the background $\mathbf{B_z}$. On the other hand, the electric field $\tilde{\mathbf{E_x}}$, called a polarization field, induced by the separation of electrons from protons is much larger than the reconnection (drifted) field E_y as pointed by Zharkova & Agapitov (2009) and Siversky & Zharkova (2009).

Polarization electric field induced by accelerated particles

In this subsection we consider this polarization electric field $\tilde{E}_x$ which is perpendicular to the current sheet and plotted in Fig. 3 as a function of x averaged over the z coordinate for various magnetic field parameters of B_{x0} and B_{y0}. The appearance of polarization electric field leads to a local non-neutrality of the plasma which becomes stronger if B_{x0} decreases or B_{y0} increases.

Particle trajectories in the presence of polarization electric field

In order to reconstruct the particle trajectories, we use the TP code, where the induced electric field $\tilde{E}_x$ obtained from PIC is added to the background electro-magnetic configuration described above. The trajectories of the two protons in the x-V_z phase plane entering the current sheet from the opposite directions are shown in Fig. 3. These trajectories are rather similar to those obtained in the TP simulations without $\tilde{E}_x$ where the "bounced" proton during the acceleration phase has a wider orbit while the "transit" proton has a narrower one producing energy distributions with two peaks.

Electrons entering from the $x < 0$ semispace have a dynamics similar to those of the "transit" protons, e.g. the electrons drift towards the midplane, become accelerated and ejected to the $x > 0$ semispace. However, the polarization field $\tilde{E}_x(x)$, which extends beyond the current sheet and has a component parallel to the magnetic field B_z, decelerates the ejected electrons. For chosen magnitudes of B_x and B_y, the majority of the electrons are unable to escape away from the RCS, instead they are dragged back to the current sheet and become indistinguishable from other electrons entered from the $x > 0$ semispace.

The electrons entering from the positive x side which are "bounced" from RCS in the absence of $\tilde{E}_x$, are able to reach its midplane if polarization field is present. In the vicinity of the midplane, the electrons become unmagnetized and oscillate with the gyrofrequency determined by B_y until they gain sufficient energy to break from the magnetic field. Although, if the electron initial velocity is small, it can be quasi-trapped inside the RCS (Fig. 3, bottom left plot). Such electrons are accelerated at the midplane, ejected from it, then decelerated outside the RCS and returned back to it because of the polarization field appeared due to protons still being accelerated in the RCS. This cycle is repeated for many times, forming electron clouds around the current sheet (Fig. 3, bottom right plot) which can be observed as a coronal source in solar flares. These clouds exist until the protons gain sufficient energy to leave the current sheet and, since the magnitude of the polarisation field $\tilde{E}_x(x)$ is smaller in the current model at $x < 0$ than at $x > 0$ (see Fig. 3, bottom plots), for electrons it is easier to escape to the $x < 0$ semispace, where the protons are ejected.

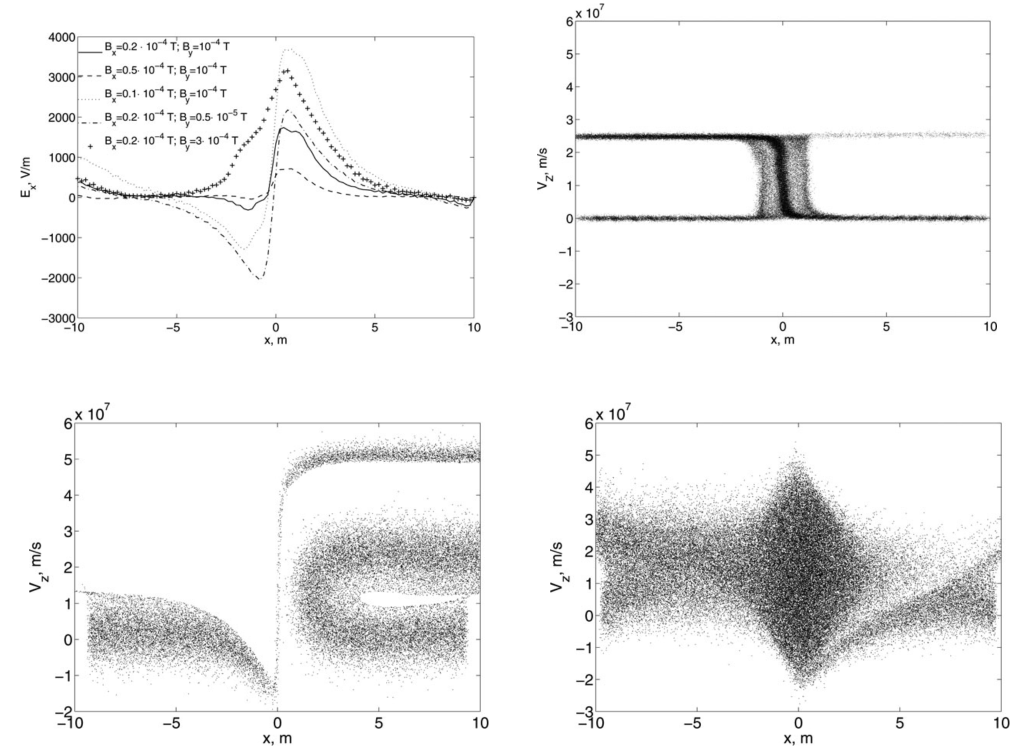

Figure 1. Top left plot: Electric field $\tilde{E}_x$ induced by particles in the PIC simulations for different values of B_{x0} and B_{y0}, for $B_{z0} = 10^{-3}$ T. Top right plot: Trajectories of protons in the V_z-x phase plane with the magnetic field magnitude of $B_{z0} = 10^{-4}$ T for the guiding magnetic field magnitude of 10^{-5} T (left bottom plot). Bottom plots: trajectories of electrons simulated for the guiding field of 10^{-4} T, $B_{z0} = 10^{-2}$ T and $B_{x0} = 10^{-4}$ T (left plot), $B_{z0} = 10^{-3}$ T and $B_{x0} = 0.5 \times 10^{-5}$ T (right plot).

4. Conclusions

The PIC simulation has shown that accelerated particles produce a strong polarisation field, $\tilde{E}_x$, caused by the charge separation of accelerated particles across the current sheet. This polarisation field is shown to be very high and leads to essential modification of the trajectories of electrons, and, to some extent, those of protons. It affects differently the "transit" particles (those which enter from and are ejected to the opposite semispaces towards the midplane) and "bounced" particles (those which enter from and are ejected to the same semispace towards the midplane) with the "bounced" protons having wider orbits than the "transit" ones. As result, in the model with polarization field the protons are ejected less asymmetrically with respect to the midplane compared to TP simulations.

The electrons, which are "bounced" in the TP approach, in the PIC simulations are dragged by the polarisation field $\tilde{E}_x$ back towards the midplane. At the same time, the "transit" electrons, which are ejected to the opposite semispace from protons in the TP approach travel from the current sheet to a distance up to 10 times the RCS thickness and then are dragged back to the RCS by the polarisation field $\tilde{E}_x$. This process results in the formation of electron clouds around current sheets which exist as long as protons are being accelerated. The clouds disappear only when protons gain sufficient energy to leave the RCS, dragging electrons with them. However, more research is required to

https://doi.org/10.1017/S1743921311007472 Published online by Cambridge University Press

investigate particle trajectories and energy spectra from the present models for different magnetic field topologies.

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