SEPARATION OF ACCELERATED ELECTRONS AND POSITRONS IN THE RELATIVISTIC RECONNECTION

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ABSTRACT

We study the acceleration of electrons and positrons in a relativistic magnetic field reconnection using a 2.5 dimensional particle-in-cell electromagnetic relativistic code. We consider a model with two current sheets and periodic boundary conditions. The electrons and positrons are very effectively accelerated during the tearing and coalescence processes of the reconnection. We found that near the X-points of the reconnection the positions of electrons and positrons differ. This separation process is in agreement with those studied in previous papers analytically or by test particle simulations. We expect that in dependence on the magnetic field connectivity this local separation can lead to global spatial separation of the accelerated electrons and positrons. A similar simulation in an electron-proton plasma with the proton-electron mass ratio $m_p/m_e = 16$ is made.

Subject headings: acceleration of particles — plasmas — relativity

1. INTRODUCTION

Magnetic reconnection is the key process in conversion of the magnetic field energy into particle kinetic energy. It is well accepted that it plays a crucial role in the Earth’s magnetotail, solar flares, and accretion disks (Priest & Forbes 2000; Drake et al. 2005; Pritchett 2006). Relativistic reconnection in electron-positron plasmas has been proposed for high-energy astrophysical phenomena, including the jets from active galactic nuclei (Lesch & Birk 1998; Larrabe et al. 2003; Wardle et al. 1998), pulsar winds (Coroniti 1990; Michel 1994; Lyubarsky & Kirk 2001), and models of gamma-ray bursts (Drenkhahn 2002a, 2002b). Relativistic reconnection and particle acceleration in pair plasmas was studied numerically for the first time by Zenitani & Hoshino (2001, 2005). The effectiveness of such an acceleration and corresponding synchrotron spectra has been computed in detail in papers by Jaroschek et al. (2004a, 2004b). Bessho & Bhattacharjee (2005) have shown that this fast reconnection is caused by off-diagonal components of the pressure tensor.

Recently, RHESSI observations of the solar flare on 2002 July 23 have revealed a separation of the gamma-ray source from any of those observed in the hard X-ray emission. This has been interpreted as a spatial separation of energetic electrons and protons (Share et al. 2003). Based on an analytical and test particle approach, Zharkova & Gordovskyy (2004) have explained this separation as an asymmetry in the acceleration of electrons and protons in the reconnecting nonneutral current sheet (see also Martens & Young 1990; Zhu & Parks 1993; Litvinenko 1996).

This separation acceleration can be even more distinct in pair plasmas since the mass of the electrons and the positrons is the same. Therefore, in this paper we use particle-in-cell modeling to study this process in the electron-positron plasma in detail.

2. MODEL

We used a 2.5 dimensional (2D3V—two spatial and three velocity components) fully relativistic electromagnetic particle-in-cell code (Saito & Sakai 2004). The system size is $L_x \times L_y = 2000\Delta \times 600\Delta = 200d_c \times 60d_c$, where $\Delta = (1)$ is a grid size, $d_c = c/\omega_{pe}$ is the electron inertial length, $c$ is the speed of light, and $\omega_{pe}$ is the plasma frequency.

Two two-dimensional current sheets with the guiding magnetic field $B_z$ are initiated along the lines $y = 150\Delta$ and $y = 450\Delta$. Periodic boundary conditions are used. The half-width of both current sheets is $10\Delta = d_c$. The initial magnetic field is (see also Karlicky & Bárt 2007)

$$ B = (B_x, B_y, B_z), $$

$$ B_x = -B_0 \quad \text{for } y < 140\Delta, $$

$$ B_x = (y - 150)B_0/10 \quad \text{for } 140\Delta \leq y \leq 160\Delta, $$

$$ B_x = B_0 \quad \text{for } 160\Delta < y < 440\Delta, $$

$$ B_x = -(y - 450)B_0/10 \quad \text{for } 440\Delta \leq y \leq 460\Delta, $$

$$ B_x = -B_0 \quad \text{for } y > 460\Delta, $$

$$ B_y = 0, \quad B_z = B_0. $$

We consider an electron-positron plasma. In each numerical cell located out of the current sheet we initiated $n_0 = 60$ electrons and $n_0 = 60$ positrons. In this region, out of the current sheet we define the plasma frequency for the time unit $\omega_{pe}^{-1}$. The time step in the computations is $\omega_{pe}\Delta t = 0.05$. The total number of particles in the model is 172 million. The initial number density is enhanced in the current sheets just to keep the pressure equilibrium in the current sheet. The particle distribution is taken as in Zenitani & Hoshino (2001), in the form of $f = \exp[-m(u_z^2 + u_y^2 + \sqrt{u_z^2 + \sqrt{u_z^2 + u_y^2}})/2T]$, where the velocity $u$ is related to the particle velocity $v$ as $u = v\gamma = v[1 - (v/c)^2]^{1/2}$, $U$ is the drift velocity, $m$ is the electron rest mass, $T$ is the plasma temperature, and $c$ is the speed of light. The mean initial thermal energy of electrons and positrons is taken as the same, $0.45\, mc^2$. We neglect any collisions, pair production, and pair annihilation of pair plasmas.

Due to our interest in the reconnection processes in relativistic plasmas with high magnetic fields, we consider cases with low-$\beta$ plasmas. The plasma beta parameter and the ratio of the electron-cyclotron and electron-plasma frequencies in the region out of the current sheets are chosen as $\beta = 0.11$, $\omega_{ce}/\omega_{pe} = 4$ (case I), and $\beta = 0.5$, $\omega_{ce}/\omega_{pe} = 1.9$ (case II). For comparison, one run was made with the parameters as in case I, but without the guiding magnetic field, i.e., $B_z = 0$.

Furthermore, the same processes are modeled in the electron-proton plasma (case III) with the proton-electron mass ratio $m_p/m_e = 16$. The proton and electron temperature is taken as the same, $T_i = T_e$. The parameters are $\beta = 0.11$ and $\omega_{ce}/\omega_{pe} = 4$. The mean initial thermal energy is $0.45\, mc^2$. 

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All computations were performed on the parallel computer OCAS (Ondřejov Cluster for Astrophysical Simulations).\footnote{See http://wave.asu.cas.cz/ocas.}

3. RESULTS

Due to the tearing mode instability, the current sheet tears into O-type islands (plasmoids) that later coalesce into larger ones. During these processes both the electrons and positrons are accelerated. Figure 1 shows an evolution of the electron distribution function $f(E)$ (for case I) in dependence on energy $E$ in the whole numerical plane (Fig. 1, top), as well as in one selected location (Fig. 1, bottom; for the location, see Fig. 4) where a much harder spectrum can be seen. While the spectral index at $\omega_{pe}t = 600$ in the whole plane is $-3.3$, in the selected location it is about $-1.9$. There are other such places, especially at locations where high-energy electrons and positrons are produced (see Fig. 4). This acceleration process is very efficient and appears to have two-steps, as shown in Figure 2. The figure shows the evolution of the number of accelerated electrons as a ratio to the total number of electrons (as a percentage) with the energy $E/m c^2 > 4$. An analysis shows that the first step of the acceleration (up to about $\omega_{pe}t = 400$) is connected with tearing processes and in the second step (after $\omega_{pe}t = 400$) the main process is the coalescence of plasmoids. The acceleration with the higher value of $\omega_{ce}/\omega_{pe} = 4$ (case I; Fig. 2, solid line) is more efficient than that with $\omega_{ce}/\omega_{pe} = 1.9$ (case II; Fig. 2, dashed line).

As in previous studies (Drake et al. 2005; Pritchett 2006; Jaroschek et al. 2004a, 2004b), the electrons and positrons are accelerated in the electric field near the X-points formed during the tearing and coalescence processes. But we found that during this acceleration process (Figs. 3 and 4) the electrons and positrons move into different locations around the O-type magnetic structures (plasmoids) and are thus spatially separated (e.g., see the region around $x = 500\Delta$ and $y = 450\Delta$ in Fig. 4). To understand this separation process, we analyzed the electric field near the X-point of the reconnection (Figs. 5 and 6). As seen here, the electrons (asterisks) are located at the borders of the areas with the enhanced ($-E_y$ and $-E_x$) and ($+E_y$ and $+E_x$). On the other hand, the positrons are located along the remaining two borders (see Fig. 3, bottom). The electric component $E_x$ along the line $y = 150\Delta$ is negative between the O-type magnetic structures (Fig. 6). But only near the X-point of the reconnection does this electric field ($E_x$) deviate from that of the inductive process.
one \(-v \times B/c\), where \(v\) is the plasma velocity (see Fig. 7, where their profiles are shown at two times, \(\omega_{pe}t = 50\) and 100). This deviation defines the diffusion region of the reconnection. As concerns the magnetic field in the early stage of the reconnection, the magnetic field component \(B_y\) is positive for the region \(x > 1000\Delta\) and negative for \(x < 1000\Delta\). The structure of the magnetic field, together with the plasma velocity pattern in the region from the X-point to the magnetic island centers, resembles that of the collapsing magnetic trap (Giuliani et al. 2005; Karlický & Bárt 2006). In such a structure the particles are also accelerated, but they are not separated, as found here near the X-points. This additional acceleration process is known as that found in contracting magnetic islands (Drake et al. 2006).

Furthermore, we made similar computations but without the guiding magnetic field component \((B_z = 0)\). In this case no separation of electrons and positrons was found. Moreover, the electric field structure was different from that presented in Figures 5 and 6.

Finally, we also made similar computations for an electron-“proton” plasma, with the electron-proton ratio \(m_e/m_p = 16\) (case III). Figure 8 shows that as in the previous cases, accelerated
electrons and protons move to different positions. Comparing case III (Fig. 2, dotted line) with case I (solid line), the number of accelerated electrons is reduced.

4. DISCUSSION AND CONCLUSIONS

The present simulations show that magnetic reconnection with a guiding magnetic field accelerates electrons to different positions around the plasmoid than positrons or "protons." If the magnetic field connectivity (in the $z$-direction) from the top and bottom parts of the plasmoid differ, then the accelerated electrons and positrons (or protons) move into quite different locations, as observed by RHESSI. The separation of particles with different electric charges is a natural consequence of the acceleration in direct electric field near the X-points of the magnetic field reconnection.

In agreement with Litvinenko (1996) and Zharkova & Gordovskyy (2004), we found that the separation process is due to a presence of the nonzero guiding magnetic field (nonneutral current sheet). Namely, our simulations with the zero guiding magnetic field show no such separations.

Zharkova & Gordovskyy (2004) have shown that the separation direction (in the present designation of the electric and magnetic field components) depends on the sign of the term $\frac{q}{\gamma}B_\parallel E_z$, where $q$ is the electron ($-e$) or positron ($+e$) charge (see relation [8] in their paper). Considering the direction of the magnetic and electric fields in our case (Figs. 5 and 6), it can be shown that the separation direction found agrees with this relation. This result also agrees with the relations presented in the paper by Litvinenko (1996).

A similar separation process is also found for the reconnection in a "proton"-electron plasma with the proton-electron mass ratio $m_p/m_e = 16$. This mass ratio is not realistic and is taken due to computer limitations. Nevertheless, we expect that such a separation process will also be confirmed by future computations for the real proton-electron mass ratio.

Comparing the acceleration process for the electron-positron (solid line) and electron-proton ($m_p/m_e = 16$, dotted line) plasma...
in Figure 2, we found that $N_{m_i}/m_e = 1/N_{m_i}/m_e = 1.18$, i.e., the number of accelerated electrons $N$ depends on the proton-electron mass ratio as $N_{i}/N_{m_i} = \frac{1}{m_i/m_e} \approx 0.0625$. If this relation is valid also for the real proton-electron mass ratio then we can write $N_{i}/N_{1838} = 1.6$, which gives enough accelerated electrons also for the real electron-proton plasma.

Comparing the present modeling with previous studies, the most similar simulation is that of Zenitani & Hoshino (2001), especially due to initial high thermal plasma energy. But in their model no guiding magnetic field, which is crucial for the particle separation, is considered. Furthermore, contrary to our start from noise level, they initiate the reconnection by magnetic field perturbation, which can influence the separation process, too. The maximum energies of accelerated electrons in both models are comparable. But in our model the reconnection process is about 3 times slower than that in Zenitani & Hoshino (2001). We think that this is due to the initial magnetic field perturbation.

Although the acceleration in the contracting magnetic islands does not separate particles of opposite electric charges, this process is important for global acceleration. But this process is even more complicated than presented in the paper by Drake et al. (2006). Namely, not only does the parallel energy of particles increase due to reflection from the ends of contracting magnetic islands (as described by relation [1] in Drake et al. 2006), but the perpendicular energy of particles $E_{\text{perp}}$ can also increase due to the betatron type of the acceleration, which follows from the conservation of the magnetic moment $\mu = E_{\text{perp}}/B$ in the region with the increasing magnetic field $B$ (see Karlický & Bártá 2006). In our simulations the contracting acceleration is time-varying; therefore, let us compare its efficiency with that of the acceleration near the X-point at one specific time. Using relation (1) of Drake et al. (2006), we derived the electric field equivalent to this process as $E_{\text{eq}} = (v_i B_x^2 m_e)/(e B_x^2)$, where $2\delta_i$ is the length of the island, $B_x$ and $B$ are the reconnecting and total magnetic fields, $v_i$ is the contracting velocity, $e$ is the electron velocity, and $m_e$ is the electron mass. For the parameters in case I at $\omega_{pef} = 100$ it gives an equivalent electric field in the contracting magnetic island $E_{\text{eq}}$ that is 1 order of magnitude lower than the electric field $E_x$ at the X-point region. This means that at this moment the acceleration near the X-point dominates over that in the contracting magnetic islands.

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