# A plasma sheet as a source of non-thermal particles — relativistic magnetic reconnection and relativistic drift kink instability in $e^{\pm}$ plasmas

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**Abstract**

We investigate a plasma sheet in astrophysical plasmas as a promising source of non-thermal particles. Two particle acceleration processes in a plasma sheet are presented by 2D particle-in-cell (PIC) simulations. First, we review a powerful acceleration process in a relativistic magnetic reconnection. In this case, particles are directly driven by the strong reconnection electric field $E_y$ around the X-type region. The obtained energy spectrum is quite hard and it is similar to power-law with the index of 1 - 1.5. Considering another 2D plane of a plasma sheet, we present another particle acceleration process which is related to current driven instability. In this case, a successive acceleration in a mid-plane channel results in the enhancement of the non-thermal particles. The physical mechanisms and characteristic properties of the two acceleration processes are discussed.

## 1. Introduction

The origins of non-thermal particles in space plasmas are a long standing problem. In order to solve them, particle acceleration processes such as double layer and shock acceleration processes have long been studied. Recently, the authors have reported a strong particle acceleration process in a relativistic magnetic reconnection [1]. The results indicate that a plasma sheet of relativistic $e^{\pm}$ plasmas, which plays a key role in an astronomical sites such as a synchrotron nebula around the crab pulsar [2], is a possible source of non-thermal particles. For further study of particle acceleration in a plasma sheet, we have investigated a cross-field instability of an $e^{\pm}$ plasma sheet. In this paper, we discuss particle acceleration processes, related to the two 2D problem of an $e^{\pm}$ plasma sheet.

## 2. Relativistic Magnetic Reconnection

First, we introduce a 2D PIC simulation of relativistic magnetic reconnection in a plasma sheet of $e^{\pm}$ plasmas. We take an extended Harris model as a prototype plasma sheet: $B_x(z) = B_0 \tanh(z/\lambda)$ and $f = n_0 \cosh^{-2}(z/\lambda) \exp\{-m[u_x^2+$

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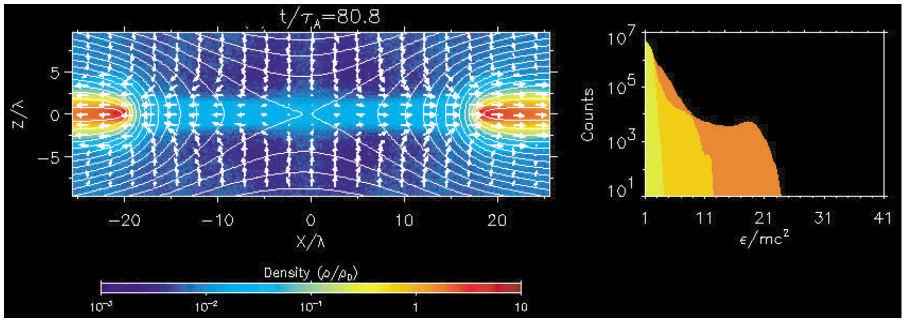


**Fig. 1.** Left : a snapshot of reconnection at $t/\tau_A = 80.6$. The magnetic field lines (white lines), plasmas' bulk flow (arrows) and plasma density (color) are presented. Right : Three stages of the energy spectra are presented: $t/\tau_A = 0.0$ (yellow), 69.3 (orange), and 80.6 (red).

$(u_y - U)^2 + u_z^2]/2T\}$, where $m$ is the mass, $T$ is the temperature parameter, $\lambda$ is the half thickness of the plasma sheet, $u = \gamma v = v/[1-(v/c)^2]^{1/2}$ is the four velocity of a particle, and $U$ is the four velocity that carries the current. The simulation region consists of $1024 \times 512$ grids in the X-Z plane and $\lambda$ is set to 10 grids. Since we take periodic boundary condition in X and double periodic in Z, the system size of a single plasma sheet is $-51.2 \le X/\lambda \le 51.2$ and $-12.8 \le Z/\lambda \le 12.8$. We assume a thin plasma sheet of $\lambda = 2r_L$, where $r_L$ is the typical Larmor radius of particles. For simplicity, we neglect any collisions, pair-production, pair-annihilation and radiation. We also assume that cyclotron frequency in the lobe is equal to the plasma frequency in the current sheet $\Omega_c = \omega_{pe}$, where $\Omega_c = eB_0/mc$ and $\omega_{pe} = [4\pi n_0 e^2/m]^{1/2}$. This means the lobe magnetic field is relatively strong so that the corresponding reconnection outflow speed, which is known to be an Alfvén velocity of the system $V_A \sim c/[1 + 2(\omega_{pe}/\Omega_c)^2]^{1/2}$, become relativistic.

In Fig. 1, we show a snapshot of the reconnection structure at $t/\tau_A = 80.6$, where $\tau_A = \lambda/V_A$ (Alfvén transit time). The left panel presents magnetic field lines (solid lines), plasmas' bulk flow (arrows) and the plasma density (color contour), respectively. The right panel shows a time development of the energy spectra of the particles in the whole simulation system. One can recognize the breakup of non-thermal edge due to particle acceleration. The acceleration site is the vicinity of the X-point and its field property is presented in Fig. 2: the ratio of of the reconnection electric field $|E_y|$ to the magnitude of the magnetic fields $|B|$. The region which satisfies the condition of $|E_y|/|B| > 1$ is a main site of acceleration, and we call it the "acceleration region (AR)". In the AR, the inflowing plasmas can be directly dragged by strong $|E_y|$. This acceleration process works as long as the reconnection process continues. The resulting non-thermal spectrum is quite hard and it is approximated by power-law with the index of 1 - 1.5.

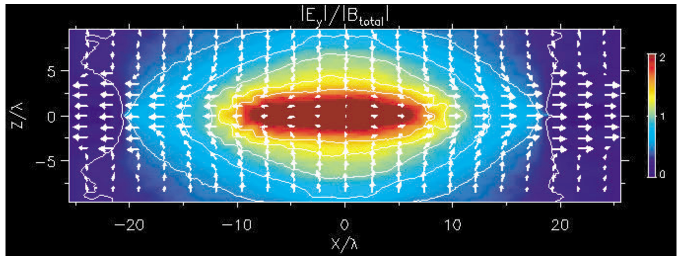


**Fig. 2.** The relative strength of the reconnection electric field $|E_y|$. The ratio of $|E_y|$ to the magnitude of the local magnetic fields $|B|$.

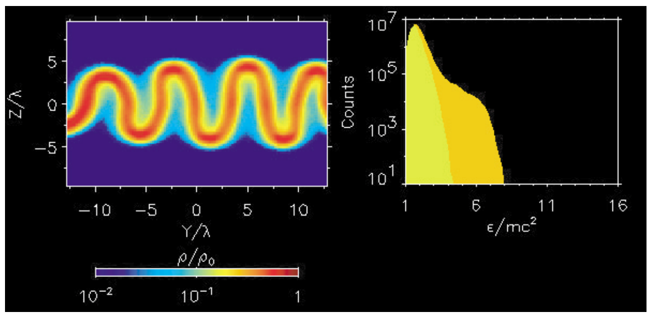


**Fig. 3.** Left : a snapshot of the current sheet at $\Omega_0 t = 384.3$. The plasma density is presented in color contour. Right: the energy spectrum ($\Omega_0 t = 384.3$; orange) and the initial energy spectrum ($\Omega_0 t = 0$; yellow) are presented.

## 3. Relativistic Drift Kink Instability

Next, we introduce a particle acceleration process in cross field plane of an $e^{\pm}$ plasma sheet. We have carried out another PIC simulation in Y-Z plane, with initial condition similar to the reconnection case. The system size is $-51.2 \leq Y/\lambda \leq 51.2$ and $-12.8 \leq Z/\lambda \leq 12.8$ for a single plasma sheet.

Fig. 3 presents the snapshot of the plasma sheet at $\Omega_0 t = 384.3$. The plasma density is presented in the left panel. The energy spectra at two simulation time are presented in the right panel. One can see a long-wavelength kink mode strongly transforms the initial plasma sheet. We have analyzed this mode and concluded that it is Relativistic Drift Kink Instability (RDKI) [3], an extension of a popular current-driven instability of Drift Kink Instability [4]. An acceleration process is activated in the non-linear stage of RDKI and the mid-plane of $Z \sim 0$ is an acceleration site. Fig. 4 shows the structure of electric field of $E_y$. The left panel is for the linear stage of RDKI ($\Omega_0 t = 347.7$), while the right panel for the non-linear stage ($\Omega_0 t = 384.3$). Note that the direction of $E \times B$ is consistent with the displacement of the plasma sheet, because $B_x > 0$ in the upper lobe and $B_x < 0$ in the lower lobe. In the non-linear stage, as a result of the plasma sheet

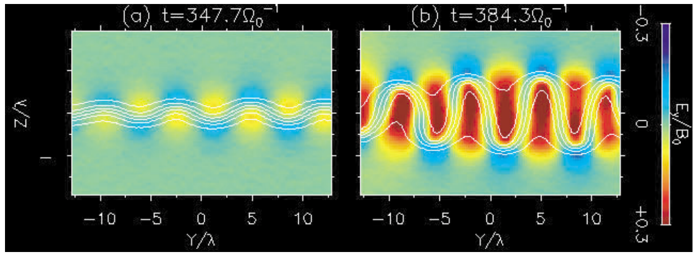


**Fig. 4.** Contour plots of electric field of $E_y$. Left: $\Omega_0 t = 347.7$, in the linear stage of the instability. Right: $\Omega_0 t = 384.3$, in the non-linear stage.

kinking, one can see a the mid-plane acceleration channel: string of red regions that satisfies $E_y > 0$ around $Z \sim 0$. Particles are successively accelerated by $E_y$ in this mid-plane channel, traveling into $\pm Y$ direction. The acceleration process continues until the kink structure collapses in later stage of simulation.

## 4. Discussion and Summary

In both 2D problems in a thin plasma sheet of $e^{\pm}$ plasmas, we found two particle acceleration processes that can generate noticeable amount of non-thermal particles. The important point of the two processes is that particles are almost directly driven by $E_y$ into the $\pm Y$ direction in the AR or in the mid-plane acceleration channel. Thus acceleration works quite *efficiently*, compared with Fermi-type acceleration mechanisms. Another important point is that higher-energy particles are more likely to be accelerated . As they are driven into the $\pm Y$ direction, they gain their energy and then their mass become much heavier by a factor of $\gamma = \varepsilon/mc^2$. This means that they are more difficult to escape from the acceleration site due to their bigger inertia, so that the energy spectrum much harder. We hope that two 2D results provide good suggestions on sources of non-thermal particles. The 3D problem of a plasma sheet should also be investigated, based on these results.


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