PARTICLE DYNAMICS IN TWO COLLIDING PLASMAS

S. Takeuchi

Faculty of Engineering, Yamanashi University, Takeda 4-3-11, Kofu 400, Japan

Abstract

A nonsteady model of magnetic field reconnection is proposed to examine an effective mechanism for the acceleration of particles to very high energy. Under the frozen-in state of the magnetic field in plasma, a time-dependent electromagnetic field configuration is exactly derived. Accordingly, it is possible to investigate dynamics of accelerated particles in the relativistic regime analytically and numerically. Due to the colliding of two plasmas, the magnetic neutral sheet is generated and the magnetic energy is converted into kinetic and internal energy of plasmas. The model will be a plausible candidate of the solar flare.

1. Introduction

Many researches with respect to magnetic field reconnection has been made on the basis of the steady-state model of the magnetohydrodynamics (MHD). Since the phenomena of the reconnection is essentially nonlinear, it is so difficult to analyze theoretically. In order to develop an understanding of basic features of the reconnection process, physical pictures between electromagnetic fields and individual plasma particles should be clear. It is, however, difficult to describe concrete image of particle dynamics by both the MHD theory and its numerical simulation.

The purpose of this article is to present a nonsteady model of the magnetic field reconnection and to theoretically and numerically examine the basic process of energy conversion from the electromagnetic fields into individual plasma particles. Under the frozen-in state of the magnetic field in plasma, the electromagnetic field configurations are explicitly derived. Accordingly, finite size plasmas moving with the magnetic field lines can be easily dealt with. In the model of magnetic field reconnection which is generated by two colliding plasmas with anti-parallel magnetic components, motions of many test particles that interact with the nonsteady electromagnetic fields are investigated by using the relativistic equation of motion.

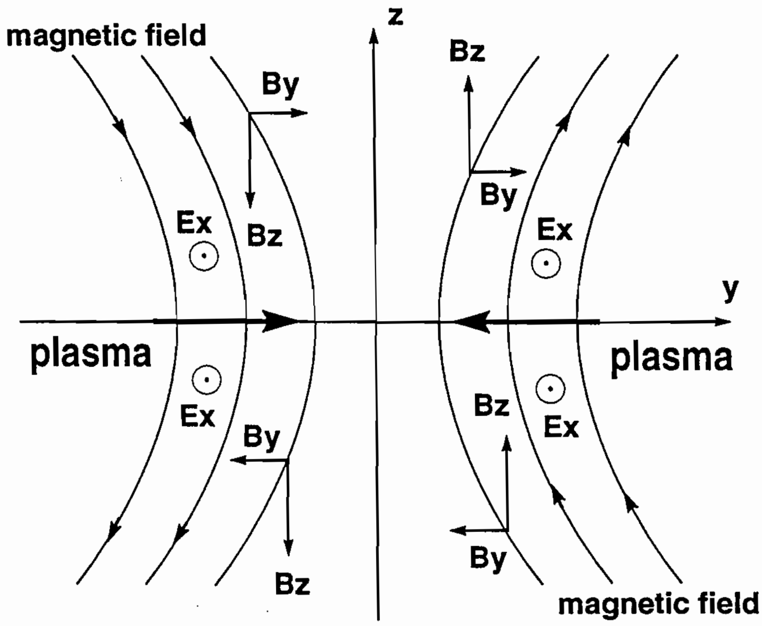

Fig. 1. Configuration of the electromagnetic fields. Two plasmas move together with magnetic filed lines under the frozen-in state and collide with each other. They have the symmetric electric fields E_x and the anti-parallel magnetic fields B_z.

2. Model of Two Colliding Plasmas

We assume that the magnetic field line moving with the plasma is described as $B_z = B_0 f(y,z,t) = B_0 f[y - vt + h(z) + s]$, here $h(z)$ denotes the configuration of the magnetic field in the z-direction and s is the phase constant. The magnetic field moves along the y-axis with the phase velocity v. By using the Maxwell equations $\nabla \cdot \mathbf{B} = 0$ and $\nabla \times \mathbf{E} = -(1/c)(\partial \mathbf{B}/\partial t)$, the magnetic field B_y and the electric field E_x are given by $B_y = -(\mathrm{d}h/\mathrm{d}z)B_z$ and $E_x = -(v/c)B_z$, respectively. In the frozen-in state, the additional condition $\mathbf{E} \cdot \mathbf{B} = 0$ must be satisfied. Then, the flux transport velocity $\mathbf{v}_E$ of the magnetic field is given by $\mathbf{v}_E = c\mathbf{E} \times \mathbf{B}/B^2$. We ignore the uniform components of the electromagnetic fields, i.e., $B_x = 0, E_y = E_z = 0$. The field configuration presented here is similar to that of the two- dimensional time-independent electromagnetic model which is proposed as a steady-state reconnection model.

As shown in Fig.1, we consider the model of two colliding plasmas under the frozen-in state. The configuration of the magnetic field can be given by an arbitrary function; we take here $f = \tanh(\eta + \psi) + 1$. Using dimensionless variables normalized by a typical length ℓ and the velocity of light c, we obtain

$$\eta_k = \tilde{y} + \beta_k \tilde{t}, \quad \psi_k = h_k(\tilde{z}) + \tilde{s}_k = \alpha_k \tilde{z}^2 + \phi_k, \tag{1}$$

then electromagnetic field components are explicitly given by

$$B_{zk} = B_{0k}[\tanh(\eta_k + \psi_k) + (-1)^k], \quad B_{yk} = -\frac{\mathrm{d}h_k}{\mathrm{d}\tilde{z}} B_{zk}, \quad E_{xk} = \frac{\partial \eta_k}{\partial \tilde{t}} B_{zk}, \tag{2}$$

where $\beta = v/c$, $\tilde{t} = (c/\ell)t$, $h_k(\tilde{z}) = \alpha_k \tilde{z}^2$, $\tilde{s}_k = \phi_k$, and $k = 1, 2$ stand for the right-hand side plasma and the left one as shown in Fig.1. Each plasma has anti-parallel component of the magnetic field B_z where $B_{01} = B_{02} \equiv B_0$. In the region near magnetic null, the magnetic neutral sheet (MNS) is generated by the colliding of the plasmas. The field configurations caused by the colliding are given by the total summation of two plasma fields:

$$B_z^t \equiv B_{z1} + B_{z2} = B_0[\tanh(\eta_1 + \psi_1) + \tanh(\eta_2 + \psi_2)], \tag{3}$$

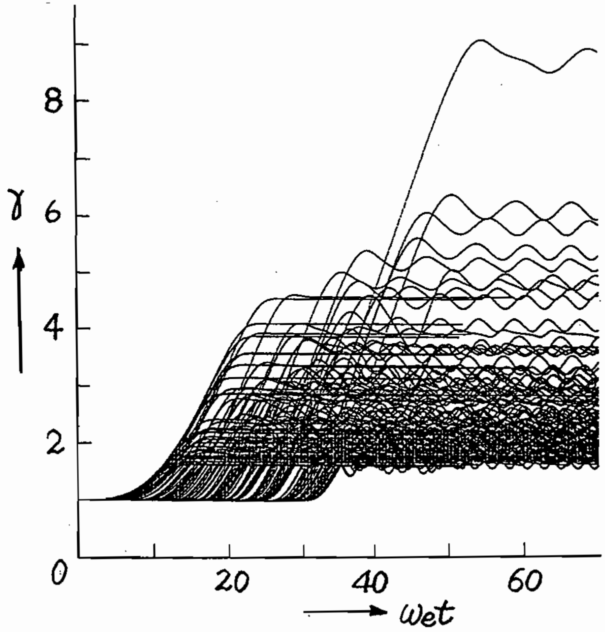

Fig. 2. Effective acceleration of the test electrons. All electrons, three hundreds particles, are randomly located near the colliding region. Some electrons are effectively accelerated in the $\tilde{x}$-direction and gain energy in a very short time interval until the energy saturation is occurred by the magnetic fields B_y and B_z.

$$B_y^t \equiv B_{y1} + B_{y2} = -2\tilde{z}B_0[\alpha_1 \tanh(\eta_1 + \psi_1) + \alpha_2 \tanh(\eta_2 + \psi_2) - \alpha_1 + \alpha_2], \quad (4)$$

$$E_x^t \equiv E_{x1} + E_{x2} = B_0[\beta_1 \tanh(\eta_1 + \psi_1) + \beta_2 \tanh(\eta_2 + \psi_2) - \beta_1 + \beta_2]. \quad (5)$$

Symmetric field configuration with respect to $\tilde{x}\tilde{z}$-plane is assumed for simplicity, i.e., $\beta_2 = -\beta_1 \equiv \beta$, $\alpha_1 = -\alpha_2 \equiv \alpha$ and $\phi_1 = -\phi_2 \equiv \phi$.

3. Numerical Calculations

The relativistic equation of motion and the energy equation of the test electron which interacts with the two electromagnetic fields are given by

$$\frac{dP_x}{d\tilde{t}} = \tilde{E}_x^t + \beta_y \tilde{B}_z^t - \beta_z \tilde{B}_y^t, \quad \frac{dP_y}{d\tilde{t}} = -\beta_x \tilde{B}_z^t, \quad \frac{dP_z}{d\tilde{t}} = \beta_x \tilde{B}_y^t, \quad \frac{d\gamma}{d\tilde{t}} = \beta_x \tilde{E}_x^t, \quad (6)$$

here $\mathbf{P} = \gamma\beta$ is the canonical momentum and $\omega_e = qB_0/mc$ is the electron cyclotron frequency, $\gamma = (1 - \beta^2)^{-1/2}$. The typical length is denoted by $\ell = c/\omega_e$. The electromagnetic fields are normalized by $(\tilde{E}, \tilde{B}) = (\mathbf{E}/B_0, \mathbf{B}/B_0)$.

Numerical calculations are carried out by using the equation of motion described above. Time evolution of γ which corresponds to energy gain of the test electrons is shown in Fig.2. All electrons, whose initial velocity components are the same as that of the flux transport velocity of the magnetic field, are randomly located near the colliding region. Since some electrons near the origin $(\tilde{y}, \tilde{z})$=(0,0) are accelerated along $\tilde{x}$-direction, the energy of such electrons linearly increase with time. As the value of γ becomes large, the accelerated electrons experience the Lorentz force $\beta_x \tilde{B}_y$ and move negative or positive $\tilde{z}$-axes away from $\tilde{x}$-axis. This causes saturation of the energy gain and change of the velocity components: the decrement of β_x, and the increment of β_y and β_z.

4. Discussion

The electromagnetic fields experienced by the test particle are given by the total electromagnetic field of two plasmas, i.e., $(B_y, B_z, E_x) \equiv (B_y^t, B_z^t, E_x^t), B^2 \equiv (B_z^t)^2 + (B_y^t)^2$. Then, the velocity components of the field transport velocity $\beta_E = v_E/c$ can be rewritten as

$$(\beta_E^y,\ \beta_E^z) = \frac{E_x^t}{B^2}(-B_z^t,\ B_y^t). \tag{7}$$

Under the frozen-in state, magnetic field lines move together with the plasma and vice versa. Therefore, we consider that the moving velocity of the plasma coincides with the flux transport velocity of the electromagnetic field. When two plasmas with the inflow velocity $\pm\beta$ approach each other from positive or negative sides of $\tilde{y}$-axis in the early stage $\tilde{t} \approx 0$, the electromagnetic fields are reduced to the following simple form:

$$B_z^t \approx 2B_0 \tanh 2\tilde{y}, \quad B_y^t \approx 4\alpha B_0 \tilde{z}, \quad E_x^t \approx 2\beta B_0. \tag{8}$$

where $\tilde{y} \approx 0$ and $\phi \approx 0$ are assumed. These fields imply that around the MNS at $\tilde{y} = 0$ non-oscillating standing electromagnetic fields are generated. We consider the case where the plasma moves along the $\tilde{y}$-axis from the negative side to the positive one. Around the $\tilde{y}$-axis, i.e., $B_y^t \approx 0$, the velocity components can be described by $(\beta_E^y, \beta_E^z) \approx (-\beta/\tanh 2\tilde{y}, 0)$, and then the velocity $|\beta_E^y|$ increases gradually as a value of $\tilde{y}$ becomes small. While, the approximation $B_z^t \approx 0$ is available around the $\tilde{z}$-axis, then the velocity components can be expressed by $(\beta_E^y, \beta_E^z) \approx (0, \beta/2\alpha\tilde{z})$. As the plasma approaches to the origin, the velocity β_E^y becomes small and β_E^z increases. Therefore, we understood that the plasma approaches to the origin along the positive and negative $\tilde{y}$-axes and leaves along the positive and negative $\tilde{z}$-axes by changing directions near the region of the MNS. Since individual test particles experience the electric field E_x^t near the MNS and are effectively accelerated in the $\tilde{x}$-direction, the frozen-in state must be removed in the colliding region.

Recently, many initial scientific papers from the Yohkoh mission, to study the high-energy phenomena caused by solar activity, are published. High-energy phenomena, whose energy level is from the soft-Xrays ($\sim$1 keV) to the γ-rays ($<$100 MeV), is observable. It is suggested that high energy electrons which are accelerated near the loop top of the solar flare move along the magnetic loops and stream into atmosphere at their footpoint.

It will be found that such high energy phenomena is interpreted by the numerical results presented here. The colliding region corresponds to the top of the solar flare. In the numerical calculation, the accelerated test electrons also have high energy from 0.5 MeV over 4 MeV within a very shot time interval. Hence, they might radiate the soft and/or hard X-ray by bremsstrahlung if they were real electrons in the solar flare. This model is an essential mechanism of high-energy electron production and will be a plausible candidate of the solar flare.

References

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