

Proton acceleration and its energy spectra during coalescence of two parallel current loops

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We investigate the plasma dynamics during coalescence of two parallel current loops by using a resistive MHD code. We investigate the orbit of many protons in the electromagnetic fields obtained from the MHD simulations. We investigate two cases of the coalescence process: co-helicity and counter-helicity. We found a bump-on-tail distribution in the same direction as the original loop current for both cases of co-helicity and counter-helicity.

Key words : solar flares, coalescence of two loops, proton acceleration

1 Introduction

Recent paper by Hurford et al. (2003) [1] presents the first gamma-ray images of a solar flare taken from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) for the X4.8 flare of 2002 July 23. The result shows that the centroid of the 2.223 MeV image was found to be displaced by 20 ± 6 arcsec from that of the 0.3-0.5 MeV, implying a difference in acceleration and/or propagation between the accelerated electron and proton population near the Sun. The fact that proton-associated gamma-ray source does not coincide with the electron-bremsstrahlung sources suggests that the protons would be accelerated in one direction by the DC electric field and could subsequently interact in spatially separated sources. Therefore it is now important to investigate in details the proton acceleration processes for different types of flares.

In this paper we investigate the plasma dynamics during coalescence of two parallel current loops [2][3] by using a resistive three-dimensional MHD simulation code, particularly paying attention to find the most effective electromagnetic fields for the production of high-energy protons.

Next we investigate the orbit of many protons in the electromagnetic fields obtained from the MHD simulations. We investigate two cases of the coalescence process: (1) co-helicity reconnection where only poloidal magnetic field produced from the axial currents dissipate and (2) counter-reconnection where both poloidal and axial magnetic fields dissipate. We found that for the proton acceleration the co-helicity reconnection is more efficient than the case of counter-helicity reconnection. The protons

can be accelerated mostly in one direction along the loop axis near where magnetic reconnection occurs.

The paper is organized as follows. In §2 we present the basic equations and simulation model. In §3 we present simulation results. In the final section we summarize our results.

2 Basic equations and simulation model

2.1 Basic equations and numerical scheme

To solve the following resistive MHD equations, we employ recently proposed *Artificial Wind* (AW) numerical scheme [4] with splitting over the spatial coordinates. The AW scheme is based on the fact that the fundamental physical invariance (Galilean or, more generally, Lorentz invariance) allows one to solve the governing equations in different steadily moving frames. Tests of ideal MHD simulation show that the AW scheme captures all the structures of MHD waves correctly without producing noticeable oscillations. The following conservative MHD equations are numerically integrated:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho V_i) = 0, \quad (1)$$

$$\frac{\partial(\rho V_i)}{\partial t} + \frac{\partial}{\partial x_j} [\rho V_i V_j + (p + B^2)\delta_{ij} - 2B_i B_j] = 0, \quad (2)$$

$$\frac{\partial B_i}{\partial t} + \frac{\partial}{\partial x_j} (V_j B_i - V_i B_j) = \frac{1}{R_m} \frac{\partial^2 B_i}{\partial x_j^2}, \quad (3)$$

$$\frac{\partial}{\partial t} \left(\frac{\rho V^2}{2} + \frac{p}{\gamma-1} + B^2 \right) + \frac{\partial}{\partial x_i} \left[V_i \left(\frac{\rho V^2}{2} + \frac{\gamma p}{\gamma-1} + 2B^2 \right) - 2B_i B_j V_j + q_i \right] = 0, \quad (4)$$

where ρ , V_i , p_i and B_i are the density, velocity, pressure and magnetic field, respectively; γ is the adiabatic constant, R_m is the magnetic Reynolds number; δ_{ij} is a unity tensor; and q_i is the dissipative energy flux. The density, pressure, velocity, and magnetic field are normalized to ρ_0 , p_0 , $\sqrt{p_0/\rho_0}$, and $B_0 = \sqrt{8\pi p_0}$, respectively.

We admit the dissipative hydrodynamic flux to be as follows

$$q_i = \frac{\partial}{\partial x_i} \left(-\frac{B^2}{3R_m} - \lambda \frac{P}{\rho} \right), \quad (5)$$

The magnetic Reynolds number $R_m = 1.3 \times 10^3$ and the heat transfer constant $\lambda = 2.5 \times 10^{-4}$ are used in simulation. Radiating boundary conditions were used for all directions.

2.2 Simulation model

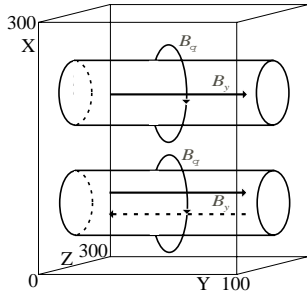


Figure 1: A schematic picture of the two parallel current loops coalescence.

Magnetic reconnection during two current loops coalescence produces strong electric field in the plasma and, as a result, charged particles can be accelerated. In this paper, we concentrate on the proton dynamics around an X-point. During two current loops coalescence, there are two types of magnetic reconnection possibly occurring: one is complete reconnection (we call here counter-helicity

case), where the B_y component is not null. Here We take the system size as $N_y = 100\Delta$ and $N_x = N_z = 300\Delta$. The two current loops ($i=1,2$) located parallel along the y -axis is assumed to be in an equilibrium state, in which the magnetic field and pressure for each loop are given as

$$B_x = q_i B_y (z - z_{ci}) / a, \quad (6)$$

$$B_y = B_{0i} e^{-\left(\frac{r_i}{a}\right)^2}, \quad (7)$$

$$B_z = -q_i B_y (x - x_{ci}) / a, \quad (8)$$

$$p_i = \left(\frac{q_i^2}{2} - \frac{q_i^2 r_i^2}{a^2} - 1 \right) e^{-2\left(\frac{r_i}{a}\right)^2} + 0.55, \quad (9)$$

The centers of the two flux tubes with a radius $a = 30$ are located at $(x_{c1}, z_{c1}) = (105, 150)$ and $(x_{c2}, z_{c2}) = (195, 150)$, respectively. The density profile is the same as the pressure. The twist parameter q_i is $q_1 = q_2 = 1$ and $B_{01} = B_{02} = 1.0$ for co-helicity, while $B_{01} = 1.0$, $B_{02} = -1.0$ for counter-helicity. The plasma beta in the center of the two loops is 0.06. Radiating boundary conditions were used for all directions.

3 Simulation results

3.1 Simulation results of two loops coalescence

We present our simulation results for two parallel current loops coalescence for co-helicity and counter-helicity cases. Due to attraction, the two initially static current loops begin to move and approach to each other. Then they meet, merge and form a new single loop. We particularly pay attention on which time period the induced electric field becomes most strongest during the coalescence, because of finding the most efficient proton acceleration phase. As a result, the most strongest electric fields can be induced just the two loops begin to merge with magnetic reconnection at about $t = 4.7\tau_A$ (Fig.2).

3.2 Proton dynamics and its energy spectra

The proton energy spectrum is more complicated. There appears a weak bump-on-tail in middle energy region (Fig.3). The magnetic field component along the reverse current is more effective for the high-energy proton production, because the guiding magnetic field plays role to keep the protons in

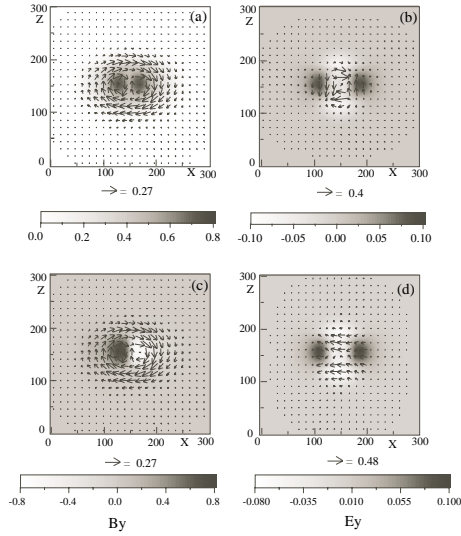


Figure 2: The electromagnetic fields at $t = 4.7\tau_A$: (a) The gray scale is B_y . The vector plot is $B_x - B_z$.(co-helicity), (b) gray scale is E_y . The vector plot is $E_x - E_z$.(co-helicity), (c) The gray scale is B_y . The vector plot is $B_x - B_z$.(counter-helicity), (d) The gray scale is E_y . The vector plot is $E_x - E_z$.(counter-helicity)

the accelerating region for a long time, while in a weak guiding field like the case of counter-helicity case the accelerated protons may escape from the strong electric field region (Fig.3). Next as seen in Fig.4 (b), strong anisotropic acceleration in the negative y-direction is observed for the co-helicity case, while for the counter-helicity case, almost symmetric acceleration in the y-direction occurs and the maximum proton velocity in the y-direction is small compared with the co-helicity case. Next we found that the high-energy proton in the negative y-direction can be produced near the center of the reversed current sheet and the middle energy proton in the positive y-direction can be accelerated near the region where the electric field E_z is strong to the positive z-direction. Therefore the protons with middle energy can be produced mostly in one loop like the right-hand loop as seen in Fig.5 (c). Moreover, for the counter-helicity case there does not appear strong anisotropic proton acceleration in the y-direction along the loop.

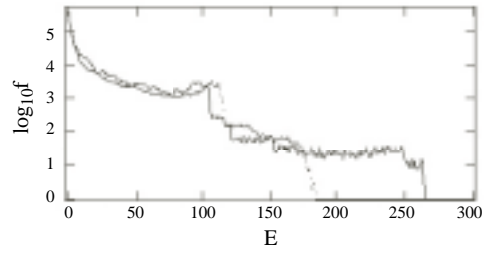


Figure 3: Proton energy spectra at $\omega_{ci}t = 1500$. The solid and dashed curves show the co-helicity and counter-helicity case, respectively. $E = (V_x^2 + V_y^2 + V_z^2)/V_A^2$.

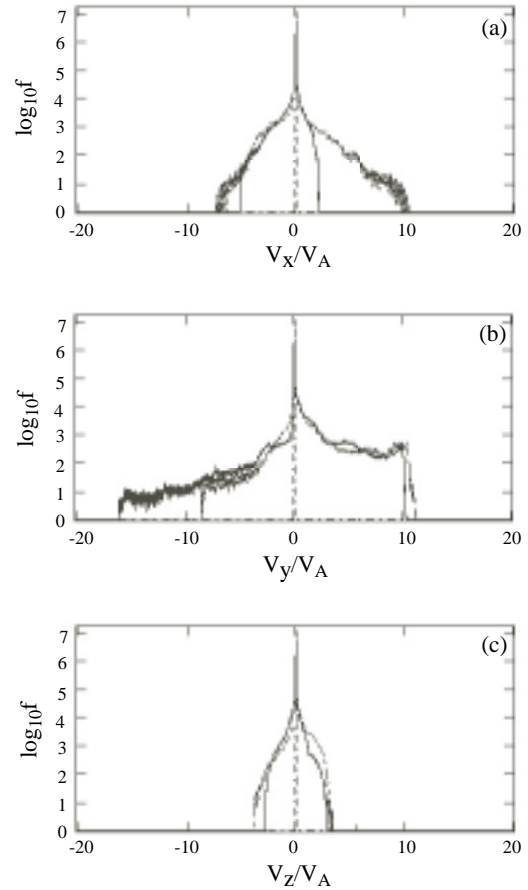


Figure 4: The proton velocity distribution function of three component, (a) V_x , (b) V_y and (c) V_z . The dot-dashed, dotted and solid curves show the initial proton velocity distribution, proton velocity distribution for the counter-helicity case and for the co-helicity case at $\omega_{ci}t = 1500$, respectively.

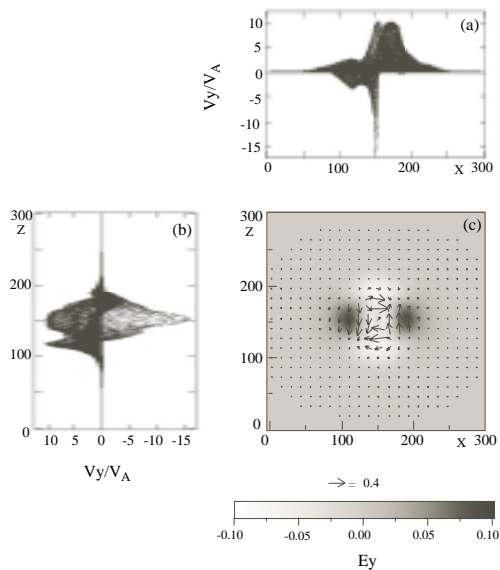


Figure 5: The phase-diagrams of protons:(a) the $x - V_y$ plane and (b) the $z - V_y$ plane at $\omega_{ci}t = 1500$. (c) The spatial distribution of the electric field E_y with gray scale and the vector plots($E_x - E_z$) at $4.7\tau_A$ for the co-helicity case.

4 Conclusions

The electromagnetic fields during the coalescence process were calculated from a three dimensional resistive MHD simulation, to find the most effective electric fields for the proton acceleration. The proton energy spectrum is neither pure exponential type nor pure power-law,because of more complicated structure of the electromagnetic fields during coalescence process.We found a bump-on-tail distribution in the positive y-direction along the original loop current for both cases of co-helicity and counter-helicity cases. We may conclude that the anisotropic proton acceleration along the loop can be realized only for co-helicity reconnection during two parallel loops coalescence.

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