PROTON ACCELERATION AND ITS ENERGY SPECTRA DURING THE COALESCENCE OF TWO CROSS CURRENT LOOPS

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We investigate the plasma dynamics during coalescence of two cross current loops 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 found that the proton acceleration is more efficient than the case of two parallel loops coalescence. It is shown that the maximum proton energy is about 25 MeV and exceeds the energy (2.223 MeV) of the observed prompt nuclear de-excitation lines of gamma-ray and the proton energy spectrum is a power-law type with an index of about 2 - 2.3. The simulation results imply that proton-associated gamma-ray sources are located near the footpoints with magnetic north polarity. We found that strong proton acceleration leading to the observed prompt line gamma-ray emissions can be realized only when there occurs the complete magnetic reconnection where both poloidal and axial magnetic fields reconnect.

Key words : Sun: flares-Sun: loop coalescence flare-Sun: proton acceleration

1 Introduction

When energetic protons accelerated during impulsive flares collide with solar atmosphere, they produce excited nuclei, which emit prompt nuclear de-excitation lines, as well as secondary neutrons and positrons that results in the delayed 2.223 MeV neutron-capture and 511 KeV positron-annihilation line emission. In most strong flare events the time profile of the prompt gamma-ray line emission is observed to be very similar to that of the bremsstrahlung hard X-rays emitted by energetic electrons. This suggests that the acceleration and propagation of the flare-accelerated protons and electrons are closely related. The most typical event among them is the 1980 June 7 flare observed by the SMM (Forrest and Chupp 1983), which flare was explained by the current loop coalescence model (Tajima et al. 1982; Sakai & Ohsawa 1987; Sakai & De Jager; 1996; Aschwanden 2002). Sakai & de Jager (1996) gave a view of the high-resolution observations of solar plasma loops with simulations of current-carrying loops and tried to arrive at the understanding of solar flare phenomena.

As proposed by de Jager (1988) and Sakai & de Jager (1991), there are three phases of acceleration in a fully developed eruptive/dynamic flare. The relevant observations regarding the first two phases are:

(1) the acceleration times of electrons and protons to energies of the order of one MeV are of the order of a second.

(2) MeV protons are accelerated nearly simultaneously with MeV electrons.

Many theoretical works (Forman et al. 1986; Simnett 1995; Sakai & de Jager 1996; Miller et al. 1997; Aschwanden 2002) to explain the above observational requirements have been done.

However, the location, size and geometry of the accelerated proton collision region remains unknown until now. Recent paper by Hurford et al. (2003) 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.

Sakai (1990a, 1990b) showed that, during 3D X-type current loop coalescence and under suitable assumptions of the size and other physical parameters in the region of acceleration, protons and electrons may be accelerated promptly (i.e., within less than 1 s) to \( \approx 100 \) GeV and \( \approx 100 \) MeV, respectively. De Jager & Sakai (1991) showed that the duration of impulsive phase bursts (5-25 s) observed during the impulsive phases of flares can be explained quantitatively by the mechanism of X-type current-loop coalescence. Sakai (1992) developed a model for long-duration gamma-ray/proton flares (the 'gradual GR/P flares') in order to explain prompt proton and electron acceleration during the impulsive phase. He determined the electric fields during the implosion phase of the current sheet from the MHD equations, and investigated the motion of test protons and electrons. Results showed that, under reasonable assumptions of the size and velocities in the reconnection area, both protons and electrons can be accelerated promptly within 1 s to \( \sim 70 \) MeV and \( \sim 200 \) MeV, respectively. However, the above previous works did not give the energy spectrum of accelerated particles.

Mori et al. (1998) investigated the behavior of protons near an X-type magnetic reconnection region by numerical simulations. The magnetic field is taken to be hyperbolic and time stationary with a uniform electric field perpendicular to the magnetic field. They also studied the effects of the magnetic field along the uniform electric field. They found from many parametric runs that the energy spectrum of accelerated protons near an X-type magnetic reconnection region is universal with a power-law spectrum \( E^{-\gamma} \), where the power-law index \( \gamma \) is about 2.0-2.2. The acceleration time of protons with the energy range of 1-20 MeV is very rapid and within \( \sim 10^5 \omega_{ci}^{-1} \) which is much less than 1 s for solar flares. Heerikhuisen et al. (2002) and Craig et al. (2002) investigated the proton dynamics under a self-consistent MHD reconnection solution and found that the proton energy spectra approximates a power law \( E^{-1.5} \) nonrelativistically, but steepens slightly at the higher energies. Hamilton et al. (2003) studied the proton energy spectra under the model fields obtained from solutions of the linearized MHD equations for reconnecting region. They showed that in some cases the energy distributions exhibit a bump-on-tail in the MeV range, but in general, the shape of the distribution is sensitive to the model parameters. The previous model fields used during coalescence process to obtain the proton energy spectrum were limited by the spatially simple configurations near the reconnection region and by no self-consistent MHD solutions.

Sakai and Shimada (2004) investigated the plasma dynamics during coalescence of two parallel current loops by using a resistive three-dimensional MHD simulation code and the orbits of test protons under the most effective electromagnetic fields obtained from the MHD simulations. They 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. They also showed that the proton energy spectrum is neither pure power-law type nor pure exponential type. They proposed one of possible scenario to explain the above recent observation as follows. The single loop is supposed to be disrupted by the mechanism recently proposed by Sakai et al. (2002), then the disrupted part of the loop with high energy protons as well as hot thermalized protons could move up and then interact with overlying other loop. The interaction between the ascending magnetized plasma blobs and other loop can lead to magnetic reconnection in the interaction region, where the proton could be accelerated more by the inductive electric field associated with the magnetic reconnection mostly in one direction along the guiding magnetic field.

In the present paper we investigate the plasma dynamics during coalescence of two cross current loops by using a resistive three-dimensional MHD simulation code developed by Sokolov et al. (1999, 2002), 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 found that the proton acceleration is more efficient than the case of two parallel loops coalescence investigated by Sakai and Shimada (2004). It is shown that the maximum proton energy is about 25 MeV and exceeds the energy (2,223 MeV) of the observed prompt nuclear de-excitation lines of gamma-ray and the proton energy spectrum is a power-law
type with an index of about 2 - 2.3. The simulation results imply that proton-associated gamma-ray sources are located near the footpoints with magnetic north polarity.

In §2 we present our methods to obtain the proton energy spectra during coalescence of two cross current loops. In §3 we present our MHD simulation results to obtain the most effective electric fields for accelerating the protons. In §4 we investigate many proton orbits under the electromagnetic fields during the coalescence to find their energy spectra. In final section we summarize our results.

2 Methods of simulations

In this section we describe two methods of simulation to obtain the energy spectrum of the protons accelerated during the coalescence of two cross current loops. Fig.1 shows a schematic picture (lower figure) of two current loops (loop1 and loop2) that are crossing with an angle of 90 degree and the coordinate system (upper figure) used in the simulation.

![Figure 1: A schematic picture (lower figure) of two current loops (loop1 and loop2) that are crossing with an angle of 90 degree and the coordinate system (upper figure).](image)

Finally we present briefly a model of two cross loops coalescence flare by using a three-dimensional resistive MHD simulation to obtain the electromagnetic fields during the loop coalescence. Next we present the simulation method to obtain the orbits of many protons under the electromagnetic fields obtained from the MHD simulations.

2.1 Resistive MHD simulation

A resistive 3-D MHD code with recently proposed Artificial Wind (AW) numerical scheme (Sokolov et al. 1999, 2002) with splitting over the spatial coordinates is employed. The basis of the AW scheme is the fact that fundamental physical invariance, Galilean (or more general, Lorentz) invariance, allows to solve the governing equation in different steadily moving frame. The principle of the AW scheme is that the frame of reference may be chosen in such a way that the flow under simulation is supersonic there. The problem of upwinding becomes trivial and considerably facilitated versions of discontinuity-capturing schemes may be employed. An extra velocity (Artificial Wind) is added to the velocity of the flow under simulation when the system of coordinates is changed.

The MHD equations are numerically solved in a conservative form as follows:

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

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

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

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

where, \( \rho, V_i, p \) and \( B_i \) are the density, velocity, pressure, and magnetic field, \( \gamma \) is the adiabatic constant, which is taken to be \( \gamma = 5/3 \), \( R_m \) is the magnetic Reynolds number, \( \delta_{ij} \) is a unity tensor and \( q_i \) is a dissipative energy flux. The density, pressure, velocity and magnetic field are normalized by \( p_0, V_0, \sqrt{p_0}/p_0 \) and \( B_0 = \sqrt{8\pi p_0} \), respectively.

For resistive MHD with a large but finite value of \( R_m \) the energy equation Eq.(4) should be obtained as a sum of the equation for plasma energy, in which the Joule heating term is present as follows: \( \frac{(\nabla \times B)^2}{(4\pi)^2\sigma} \) and the equation for magnetic energy...
which is given by the Eq.(4) multiplied by the magnetic field $B_i/(4\pi)$, all the variables are not normalized here and $\sigma$ is a conductivity. The dissipation of the magnetic field energy is hence given by the term as follows: $c^2/(4\pi)^2 B_i \Delta B_i$. So in the Eq.(4) for the total energy the Joule heating is compensated by the magnetic energy dissipation in a following way:

$$\frac{c^2}{(4\pi)^2} [B_i \Delta B_i + (\nabla \times \mathbf{B}) \cdot \mathbf{B}] = \frac{c^2}{(4\pi)^2} \nabla \cdot \left[ \mathbf{B} \times \nabla \times \mathbf{B} \right].$$

So the resistive dissipation in the equation of energy in present only in a form of the additional dissipative energy flux, which, in normalized variables, may be written as follows: $q_i^{(m)} = \frac{r_i}{\lambda_i} \frac{\partial}{\partial x_i} (2B_i B_j - B^2 \delta_{ij})$. The dissipative energy flux due to heat transfer may also be taken into account in a usual form $q_i^{(h)} = \lambda_i \frac{\partial}{\partial x_i} \frac{B^2}{\rho}$. For the sake of simplicity here we fully neglect the non-diagonal part of dissipative energy transfer tensor and substitute all the tensors in $q_i$ for unity tensors: $B_i B_j = B^2 \delta_{ij}/3$, $\lambda_{ij} = \lambda_0 \delta_{ij}/3$. The numerical simulation shows that the influence of the dissipative energy flux is insignificant, so we do not try to take it more carefully into account. Finally we admit the dissipative hydrodynamic flux to be as follows:

$$q_i = \frac{\partial}{\partial x_i} \left( - \frac{B^2}{3\lambda m} - \lambda \frac{B^2}{\rho} \right).$$

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.

Here we take a system size as $N_x = 300$ and $N_y = N_z = 200$, as shown in Fig.1. The two current loops where the loop1 is located parallel along the z-axis, while the loop2 is located parallel along the y-axis. Both loops are assumed to be in an equilibrium state, in which the magnetic field and pressure for each loop are given as

$$B_x = q_2 B_{02} \frac{(z - z_{c2})}{a} e^{-\frac{(z - z_{c2})^2}{a^2}} + q_1 B_{01} \frac{(y - y_{c1})}{a} e^{-\frac{(y - y_{c1})^2}{a^2}},$$

$$B_y = B_{02} e^{-\frac{(z - z_{c2})^2}{a^2}} - q_1 B_{01} \frac{(x - x_{c1})}{a} e^{-\frac{(x - x_{c1})^2}{a^2}},$$

$$B_z = B_{01} e^{-\frac{(y - y_{c1})^2}{a^2}} - q_2 B_{02} \frac{(x - x_{c2})}{a} e^{-\frac{(x - x_{c2})^2}{a^2}},$$

$$p_i = \left( \frac{a^2}{2} - \frac{a^2}{2} - 1 \right) e^{-2\frac{<(\mathbf{B})^2>}{a^2}} + 0.55,$$

where $r_1 = \sqrt{(x - x_{c1})^2 + (y - y_{c1})^2}$, $r_2 = \sqrt{(x - x_{c2})^2 + (z - z_{c2})^2}$, and the centers of the two flux tubes with a radius $a = 30$ are $(x_{c1}, y_{c1}) = (105, 100)$ and $(x_{c2}, z_{c2}) = (195, 100)$. The density profile is the same as the pressure. The twist parameter $q_i$ is $q_1 = q_2 = 1$ and $B_{01} = -1$ and $B_{02} = 1.0$. The plasma beta $\beta$ in the center of the two loops is 0.06.

### 2.2 Simulation of proton dynamics

By using the electromagnetic fields obtained from the above MHD equations during coalescence of two parallel current loops, we investigate the protons dynamics to obtain their energy spectrum. The normalized relativistic equations of the motion of a proton is given by

$$\frac{d\mathbf{u}}{dt} = \mathbf{E} + \frac{\mathbf{u} \times \mathbf{B}}{\gamma},$$

$$\frac{d\mathbf{x}}{dt} = \frac{\mathbf{u}}{\gamma},$$

where the proton velocity $\mathbf{v} = \gamma^{-1} \mathbf{u}$, the electric field $\mathbf{E}$, and the magnetic field $\mathbf{B}$ are normalized by Alfvén velocity $V_A$, $E_0 = V_A B_0/c$, and $B_0$, respectively. The time is normalized by the proton cyclotron frequency $\omega_c$, and the length is normalized by the distance over which the fields are changed across the loop radius ($a$), respectively. The Lorentz factor $\gamma$ is given by $\gamma = (1 + A^2 u^2)^{1/2}$, where $A = V_A/c$. The parameter $R$ in Eq.(3) is defined by $R = V_A/\omega_c a$. In our simulation we take $A = 1/300$ and $R = 10^{-8}$.

To advance particle under the guidance of electric and magnetic fields through solving the motion equation numerically, we used a centered-difference form of the Newton-Lorentz equations of motions (Buneman 1993; Birdsall & Langdon 1991), namely

$$\mathbf{u}^{new} - \mathbf{u}^{old} = \frac{q \delta t}{m} \left( \mathbf{E} + \frac{1}{2} \frac{\partial}{\partial t} [\mathbf{u}^{new} + \mathbf{u}^{old}] \times \mathbf{B} \right),$$

where $q$ is the charge of a particle, $m$ is the mass of a particle, and $\delta t$ is the calculate time step, respectively. As it stands, the equation for $\mathbf{u}^{new}$ is implicit. We choose the method proposed by Boris (1970) to obtain a simpler explicit solution using several steps.

The protons are randomly distributed with one proton per cell. The initial velocity distribution function for protons is Maxwellian with the thermal velocity $v_{th} = 0.4 V_A$. The simulation time step is $\omega_c \delta t = 0.05$. The boundary conditions for protons are open in the x-, y- and z-directions.
3 Simulation results of two cross loops coalescence

The basic physical evolution of reconnection between two cross loops was investigated by several authors (see, Sakai 1990b; Sakai & de Jager 1997; Linton et al. 2001). Each of the two cross current loops is in an equilibrium state as long as the distance between them is much greater than loop radius \(a\). While the loops approach to each other, they are no longer in the equilibrium state and the whole non-equilibrium system tends to a new equilibrium state. In more details, due to attraction, the two initially static current loops begin to move and approach to each other. Then they meet, merge, with sling-shot magnetic reconnection. We mention here that only when there occurs the complete magnetic reconnection where both poloidal and axial magnetic fields reconnect, high energy protons are generated.

Here we present the simulation results of dynamics of two cross current loops, especially paying attention to where and which stage the most strong electric fields are formed to accelerate protons. Fig. 2 shows the time evolution of the isosurface of total magnetic field intensity with \(|B| = 0.26\) during the collision of two current loops: (a) \(t = 0\), (b) \(t = 35\tau_A\), (c) \(t = 59\tau_A\), and (d) \(t = 82\tau_A\). As shown later, the most strong electric field appears at \(t = 59\tau_A\) shown in Fig. 2(c) where magnetic reconnection occurs. Therefore we investigate the spacial structures of the electric and magnetic fields at \(t = 59\tau_A\) shown in Fig. 2(c).

Figs. 3 shows the spacial structures of the electromagnetic fields at \(t = 59\tau_A\) in Fig. 2(c) that are used in the calculation of test proton orbits. Fig. 3(a) shows \(B_x\) (gray scale) and vector plot of \(B_y-B_z\) on \(x = 150\). Fig. 3(b) shows \(B_y\) (gray scale) and vector plot of \(B_z-B_x\) on \(y = 100\). Fig. 3(c) shows \(E_x\) (gray scale) and vector plot of \(E_y-E_z\) on \(x = 150\). Fig. 3(d) shows \(E_y\) (gray scale) and vector plot of \(E_x-E_z\) on \(y = 100\).

The most important electric field leading to the proton acceleration is the parallel component to the local magnetic field that is generated near the region where magnetic reconnection occurs due to finite resistivity. To find such a region, we calculate the spacial value of the scalar product \(E \cdot B\). Fig. 4(a) shows the spacial value of the scalar product \(E \cdot B\) in the \(x-z\) plane on \(y = 100\) at \(t = 59\tau_A\). Fig. 4(b) shows the spacial value of the scalar product \(E \cdot B\) in the \(y-z\) plane on \(x = 150\) at \(t = 59\tau_A\). The black
region shows that the induced electric field is almost parallel to the local magnetic field, while the white region shows the region where the electric field is perpendicular to the local magnetic field. Therefore we conclude from the MHD simulation that near the magnetic reconnection region there appears strong longitudinal electric field along the local magnetic field that may play an important role for the proton acceleration.

4 Proton acceleration and its energy spectrum

In this section we present simulation results of dynamics of many test protons under the MHD electromagnetic fields at \( t = 59\tau_A \) discussed in the previous section. First of all we present the proton energy spectra in Fig.5, where the energy \( E \) is normalized as \( E = (V_x^2 + V_y^2 + V_z^2) / V_A^2 \).

Fig.5(a) shows the proton energy spectra at \( \omega_{ci}t = 500 \) where the power law index is about 3.6 in the high energy region. Fig.5(b) shows the proton energy spectra at \( \omega_{ci}t = 1500 \), where the power law index is about 2.3 in the high energy region. Fig.5(c) shows the energy spectra at \( \omega_{ci}t = 2500 \), where the power law index is about 2.0 in the high energy region. If we take the Alfvén velocity as about 1000 km, then the energy \( E = 10^2, 10^3 \) correspond to 1 MeV and 10 MeV, respectively. The maximum proton energy reaches about 25 MeV at \( \omega_{ci}t = 2500 \).

Fig.6 shows the phase space plots at \( \omega_{ci}t = 2500 \) in Fig.6, where Figs.6(a)-(c) show the x-direction, y-direction, and z-direction, respectively. As seen in Fig.6(b), the protons in the loop 2 can be accelerated to the negative y-direction, while the protons in the loop 1 can be accelerated to the positive z-direction, as seen in Fig.6(c). The reason why the protons in the loops can be accelerated in one direction is investigated in the following analysis.

In Fig.7 we show the phase space plots of protons at \( \omega_{ci}t = 2500 \), where Fig.7(a) shows the plot of \( x-V_y \) and Fig.7(b) shows the plot of \( z-V_y \). Fig.7(c) show the spatial structure of the electric field, \( E_y \) (gray scale) and the vector plot of \( E_x - E_z \) on \( y = 100 \), where the elliptic region corresponding to Fig.4(a) show the region where the proton acceleration is dominant in the negative y-direction. In Fig.8 we show the phase space plots of protons at \( \omega_{ci}t = 2500 \), where Fig.8(a) shows the plot of \( y-V_y \) and Fig.8(b) shows the plot of \( z-V_y \). Fig.8(c) show the spatial structure of the electric field, \( E_y \) (gray scale) and the vector plot of \( E_x - E_z \) on \( x = 150 \), where the elliptic region corresponding...
Figure 6: Proton velocity distribution functions of (a) the x-direction, (b) y-direction, and (c) z-direction at $\omega_{ci}t = 2500$. The protons in the loop 2 can be accelerated to the negative y-direction, while the protons in the loop 1 can be accelerated to the positive z-direction.

to Fig.4(b) shows the region that the proton acceleration is dominant in the negative y-direction. As seen in the elliptic region the electric field vectors are dominantly to the negative y-direction. From the above analysis we conclude that the protons in the loop 2 are accelerated mostly to the negative y-direction.

Next we examine the protons in the loop 1. Fig.9 shows the phase space plots of protons at $\omega_{ci}t = 2500$, where Fig.9(a) show the plot of $x-V_z$ and Fig.9(b) show the plot of $y-V_y$. Fig.9(c) shows the spatial structure of the electric field, $E_z$ (gray scale) and the vector plot of $E_x-E_y$ on $z = 100$, where the elliptic region corresponding to Fig.4(a) shows the region of the loop 1 that the proton acceleration is dominant to the positive z-direction. Fig.10 shows the phase space plots of protons at $\omega_{ci}t = 2500$, where Fig.10(a) shows the plot of $y-V_y$ and Fig.10(b) shows the plot of $z-V_z$. Fig.10(c) shows the spatial structure of the electric field, $E_x$ (gray scale) and the vector plot of $E_y-E_z$ on $x = 150$, where the elliptic region corresponding to Fig.4(b) shows the region where the proton acceleration is dominant to the positive z-direction along the loop 1. From the above analysis we conclude that the protons in

Figure 7: The phase space plots of protons at $\omega_{ci}t = 2500$: (a) $x-V_y$ and (b) $z-V_y$. (c) The spacial structure of the electric field, $E_y$ (gray scale) and the vector plot of $E_x-E_z$ on $y = 100$, where the elliptic region corresponding to Fig.4(a) shows that the proton acceleration is dominant.

Figure 8: The phase space plots of protons at $\omega_{ci}t = 2500$: (a) $y-V_y$ and (b) $z-V_y$. (c) The spacial structure of the electric field, $E_x$ (gray scale) and the vector plot of $E_y-E_z$ on $x = 150$, where the elliptic region corresponding to Fig.4(b) shows that the proton acceleration is dominant.
the loop 1 are accelerated mostly to the positive z-direction.

Figure 9: The phase space plots of protons at $\omega_c t = 2500$: (a) $x-V_z$ and (b) $y-V_y$. (c) The spacial structure of the electric field, $E_z$ (gray scale) and the vector plot of $E_x - E_y$ on $z = 100$, where the elliptic region corresponding to Fig.4(a) shows that the proton acceleration is dominant.

Therefore we obtain an important result about the direction of the proton acceleration during the two cross loop coalescence, as shown in Fig.1. The proton-associated gamma-ray sources are located near two foot points with magnetic north polarity. If one of the axial currents along the loops flows in the opposite direction, then the magnetic reconnection becomes very weak, resulting in no strong proton acceleration. If the loop 1 has a different magnetic polarity from the case as shown in Fig.1, namely if the axial magnetic field $B_z$ in the loop 1 has an opposite direction, then the magnetic reconnection occurs only for the poloidal components for both current loops. Therefore the electromagnetic fields during the coalescence also becomes weak, resulting in no strong proton acceleration generating the observed line gamma-ray emissions. In summary strong proton acceleration leading to the observed prompt line gamma-ray emissions can be realized only when there occurs the complete magnetic reconnection where both poloidal and axial magnetic fields reconnect.

5 Conclusions

We have investigated the behavior of protons near magnetic reconnection region during two cross loops coalescence. The electromagnetic fields during the coalescence process were calculated form a three-dimensional resistive MHD simulation, to find the most effective electric fields for the proton acceleration. As the result by Mori et al. (1998) who showed that the energy spectrum of accelerated protons near X-type magnetic reconnection regions is universal with a power-law spectrum $E^{-\gamma}$, where the power-law index $\gamma$ is about 2.0-2.2, the proton energy spectrum is power-law type with the index of about 2-2.3. We found that the proton acceleration is more efficient than the case of two parallel loops coalescence (Sakai & Shimada 2004). It was shown that the maximum proton energy is about 25 MeV and exceeds the energy (2.223 MeV) of the observed prompt nuclear de-excitation lines of gamma-ray. The simulation results imply that proton-associated gamma-ray sources are located near the footpoints with magnetic north polarity. We found that strong proton acceleration leading to the observed prompt line gamma-ray emissions can be realized only when there occurs the complete magnetic reconnection where both poloidal and axial magnetic fields reconnect.
References


[27] Sokolov, I.V., Timofeev, E.V., Sakai, J.I., & Takayama, K. 1999, Shock waves, 9, 423
