Particle Acceleration by Turbulent Magnetohydrodynamic Reconnection

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Test-particle acceleration is studied in a two-dimensional, turbulent magnetohydrodynamic simulation whose initial magnetic field configuration is a periodic sheet pinch. Some test particles become trapped near large electric field in the reconnnection region for approximately an Alfvén transit time. The maximum speed attained is consistent with an analytic estimate which depends on the reconnection electric field, the Alfvén speed, and the ratio of Larmor period to the Alfvén transit time.

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Acceleration to high energies of a small fraction of the particles in a plasma is familiar in space physics, astrophysics, and fusion physics. Two examples are the production of energetic particles in solar flares and in planetary magnetospheres during magnetic substorms. Giovanelli,[1] Dungey,[2] Sweet,[3] Parker,[4] and others suggested that particles can be accelerated to high energies by strong electric fields which might arise near X-type magnetic neutral points. The question of whether strong electric fields exist near such neutral points has led to the study of magnetohydrodynamic (MHD) reconnection. Conclusions about the intensity of the self-consistent electric field near the X point and, therefore, the "rate of reconnection" vary considerably in reconnection models.[5] The collisional tearing instability,[6] Parker-Sweet mechanism,[3,7] and Petschek's model[8] predict values of reconnection rates which decrease at high conductivity.

The effects of turbulence in analytical and computational models have often been excluded by assuming that the background magnetic field is smooth initially and that perturbations are symmetric and/or infinitesimal. There is indication[9-11] that finite-amplitude fluctuations can lead to turbulence in X-point dynamics, thereby elevating reconnection rates. Consequently, turbulent reconnection might maintain strong X-point electric fields (and the possibility of significant particle acceleration) at high conductivity.

The question of whether a subpopulation of plasma particles might be effectively accelerated by the reconnection-zone electric field has also been extensively studied.[12-17] Typically, one calculates trajectories of "test-particles" in model MHD magnetic and electric fields. Although the electric field is usually included only parametrically, there has been at least one study[18] of test-particle orbits in the dynamic electric fields of a symmetric, forced nonturbulent MHD simulation. It is generally found that test particles do not spend much time near X-type neutral points, but can be trapped easily near O-type neutral points.[12,14] This is crucial in assessing the importance of reconnection as a particle accelerator. In nonsteady incompressible simulations, strong accelerating electric fields do not appear near O points which are the centers about which reconnected flux gathers after emerging from the reconnection zone. A long residence time near this type of O point is unlikely to produce significant particle acceleration. The short residence time of particles near the X-point region has been viewed as a limitation on the efficiency of the X-point acceleration mechanism.

In this Letter, we describe an analysis of particle orbit tracing in MHD fields which evolve and reconnect in the presence of finite-amplitude fluctuations. We find that turbulent fluctuations appearing near the reconnection zone can trap test particles in the strong electric field region for long enough times to produce significant acceleration. Consequently the turbulent X-point mechanism is an efficient accelerator.

The fields in which the test particles propagate are produced by a spectral-method, incompressible MHD simulation technique that has been described in detail elsewhere.[9,10] The magnetic field $\vec{B}$ and fluid velocity field $\vec{v}$ lie in the x,y plane and vary in that plane, all quantities being independent of the third coordinate, z. Thus, the electric current density, magnetic vector potential, fluid vorticity, and MHD electric field each have only single components in the z direction, designated J, a, ω, and E, respectively. The familiar dimensionless units[9,19] include an arbitrary length scale, L, a characteristic Alfvén speed, V_a, and a transit time for unit distance $\tau = L/V_a$.

A 128^2 spectral truncation and an explicit time step of $\frac{1}{512}$ were used. The runs lasted 10 Alfvén times. The dimensionless fluid and magnetic Reynolds numbers (reciprocals of the dimensionless viscosity, ν, and resistivity, μ) were each equal to 1000 in these simulations. The values of $\omega(\vec{k},t)$ and $a(\vec{k},t)$ for all values of two-dimensional wave vectors retained were stored every $\Delta\tau = \frac{10}{512}$ Alfvén times. The reconnection process is modeled as an unforced, turbulent initial value problem in which at $t=0$ magnetic energy resides almost entirely in a small number of Fourier modes that describe two oppositely directed neutral sheets. Turbulent reconnection is triggered by adding at $t=0$ a small but finite level of broadband random-phase "noise" perturbations.

Test particles were introduced into the simulation fields at $t=0$. Their position $\vec{X}$ and three-dimensional velocity $\vec{U}$ were then advanced in time and space according to $d\vec{X}/dt = \vec{U}$ and

$$d\vec{U}/dt = \alpha(\vec{U}\times\vec{B}+\vec{E}), \tag{1}$$

where $\alpha = \Omega\tau$, $\Omega = ZeB/mc$ is the nominal test particles gyrofrequency, and $\vec{E} = -\vec{v}\times\vec{B}+\mu\vec{J}$ is the MHD electric field.

Equation (1), written with particle velocity in units of Alfvén speed, emphasizes the role of the constant α in coupling the natural units of particle motion to those of MHD turbulence. Particle acceleration is entirely due to the z component of electric field. The implementation of the particle-pushing algorithm uses the fact that the z component of Eq. (1) implies

$$U_z + \alpha a = \text{const.} \tag{2}$$

This is an expression of the constancy of the z component of canonical momentum and allows the effect of the electric field to be incorporated implicitly through the space and time dependence of the vector potential. To ensure that the particles sample the fields in the detail afforded by the high-resolution MHD simulation, we employed a two-dimensional cubic-spline interpolation procedure to calculate field values at particle positions. The fields were also linearly interpolated in time; hence the electric field is constant between independent snapshots of the MHD simulation. Time integration of the x and y components of Eq. (1) was done by a fourth-order Runge-Kutta method. The time steps were chosen to be much less than the time between frames of the MHD fields to give good resolution of the particle gyromotion.

The first run we describe consists of 500 particles randomly distributed in space, each moving with the unit Alfvén speed at 45° pitch angle, but with randomly chosen gyrophase. The value of α is 643, so that the characteristic gyroradius is much less than the unit cell of the MHD simulation. Figure 1 shows magnetic field line plots in the area around the lower of the two current sheets at several times. New magnetic islands are appearing because of the reconnection process. Furthermore, since the same field lines are plotted in each frame [same values of $a(x,y)$], it is clear that magnetic flux is being removed from the strong field regions above and below the current sheet.

Figure 1 also shows the position of three of the test particles superimposed on the field lines at each time. These particles were selected because of their

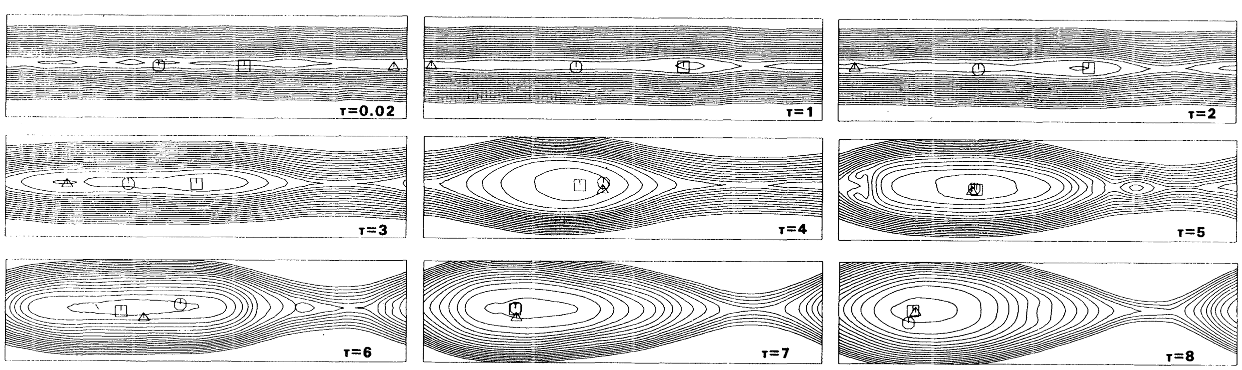

FIG. 1. Magnetic field line plots in the area of the lower current sheet at several times. The positions of three particles are indicated by the symbols: The triangle is particle No. 382, the circle is particle No. 358, and the square is particle No. 281. The contours label the same vector potential values in each panel.

significant energy gain, and because their trajectories were typical of particles gaining energy along either the upper or lower sheets. Throughout the run, most of the particles are undergoing relatively unperturbed gyromotion in the strong magnetic field regions away from the reconnection zones near the upper and lower X points. However, Fig. 2 shows that the particle energy distribution changes considerably during the run in that a small number of particles, including the three in Fig. 1, are accelerated to thousands of times their initial energy. It is apparent in Fig. 1 that the particles were trapped within small "magnetic bubbles" in the reconnection zone which are turbulent fluctuations of the magnetic field.

Analysis of the MHD simulation[11] suggests that these fluctuations are characteristic of reconnection triggered by finite-amplitude turbulence. The bubbles produce multiple X points within the reconnection zone which itself remains centered about a single filament of electric current density. Once formed, these bubbles move outward from the reconnection zone with the exhaust velocity of the fluid jets ($\simeq 0.85\, V_a$).

The trapped particles move with the bubbles, cross the strong electric field region where they are accelerated, and enter the reconnected island region around an O point. Within the large island, where the reconnection electric field is weak, particles experience less acceleration. In fact, some particles lose energy there, presumably due to adiabatic deceleration in the growing magnetic island. This is illustrated in Fig. 3 by the time history of the kinetic energy of the particles identified in Fig. 1.

The physics of the particle trapping and acceleration is easily understood. Each small magnetic bubble is a trapping center for test particles. In this simulation, particles in the reconnection zone experience a fluctuating electric field with average magnitude of $\epsilon \simeq 0.1$ (in units of $B_0 V_a$). Particles trapped in a bubble are entrained in the high-E region for about one Alfvén transit time.

From the conservation law [Eq. (2)] it follows that if a particle spends a unit time in a reconnection electric field, ϵ, its velocity will change by $\Delta V_z \simeq \epsilon\alpha$. With $\alpha = 643$, the upper limit to the velocity is about 64. Note that in Fig. 3, particle No. 382 reaches a speed of about 60 which is the highest we have found for particles in this simulation. A preliminary test of this scaling was performed using a second set of 500 particles with $\alpha = 321.5$. The highest speed attained was about 30.

If we assume the validity of this scaling and neglect the initial speed of the test particles, the maximum kinetic energy is $\epsilon_{\max} = m(\Delta V_z)^2/2 = \epsilon^2\alpha^2 m/2$, where ϵ is in units of V_a^2. This is equivalent to

$$\epsilon_{\max} = 0.5 m V_a^2 [\epsilon (L\omega_p/c)(Z/Z_0)(m_0/m)]^2, \tag{3}$$

where ω_p, Z_0, and m_0 are the plasma frequency, charge state, and ion mass of the background plasma. Equation (3) assumes that particle motion in the z direction is unbounded. If the acceleration

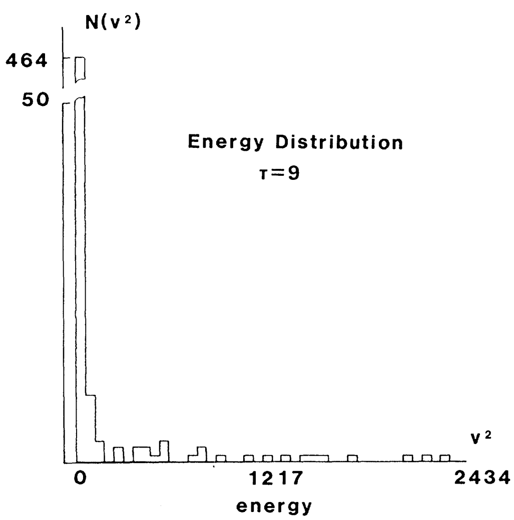

FIG. 2. Particle energy distribution at $t = 9$, indicating that most particles have gained little energy; but a small high-energy population has been formed.

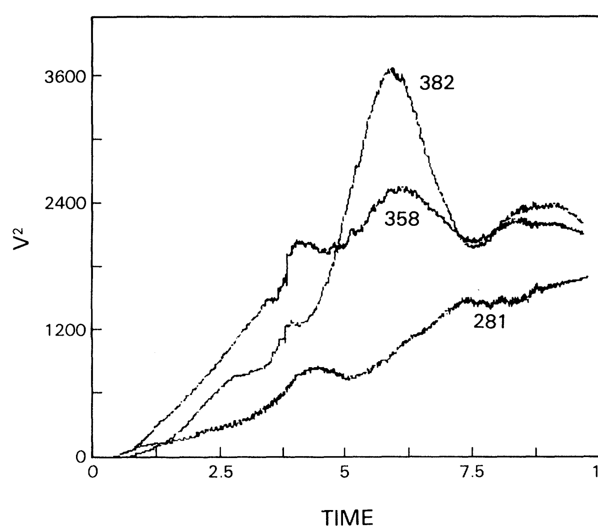

FIG. 3. The time history of the kinetic energy of particles No. 382, No. 358, and No. 281 (cf. Fig. 1).

acts only until the particles have traveled a distance L in the z direction, then the estimated duration of the acceleration process becomes $\tau^* = [2/(\epsilon\alpha)]^{1/2}$, and the maximum energy is

$$\epsilon_{\max} = mV_a^2[\epsilon(L\omega_p/c)(Z/Z_0)(m_0/m)].$$

Note that this is proportional to the charge of the test particles, but independent of their mass.

These simulations indicate that turbulent fluctuations in a reconnecting magnetofluid can trap test particles in the strong electric field region and accelerate them to speeds of order $\epsilon\Omega\tau V_a$.

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[1]R. G. Giovanelli, Mon. Not. Roy. Astron. Soc. **107**, 338 (1947).

[2]J. W. Dungey, *Cosmic Electrodynamics* (Cambridge Univ., Cambridge, 1958).

[3]P. Sweet, in *Electromagnetic Phenomena in Cosmical Physics,* edited by B. Lehnert (Cambridge Univ., Cambridge, 1958), and Nuovo Cimento Suppl. **8**, 188 (1958).

[4]E. N. Parker, Astrophys. J. Suppl. Ser. **8**, 177 (1963).

[5]E. N. Parker, *Cosmical Magnetic Fields* (Clarendon, Oxford, 1979).

[6]H. Furth, J. Killeen, and M. Rosenbluth, Phys. Fluids **6**, 459 (1963).

[7]E. N. Parker, J. Geophys. Res. **62**, 509 (1957).

[8]H. Petschek, in *AAS/NASA Symposium on the Physics of Solar Flares,* edited by W. N. Hess (National Aeronautics and Space Administration, Washington, D.C., 1964), p. 425.

[9]W. H. Matthaeus and D. C. Montgomery, J. Plasma Phys. **25**, 11 (1981).

[10]W. H. Matthaeus, Geophys. Res. Lett. **9**, 660 (1982).

[11]W. H. Matthaeus and S. L. Lamkin, Phys. Fluids (to be published).

[12]B. U. Ö. Sonnerup, J. Geophys. Res. **76**, 8211 (1971).

[13]T. W. Speiser, J. Geophys. Res. **72**, 3919 (1967).

[14]D. P. Stern, J. Geophys. Res. **84**, 63 (1979).

[15]J. S. Wagner, J. R. Kan, and S.-I. Akasofu, J. Geophys. Res. **84**, 891 (1979).

[16]V. M. Vasyliunas, J. Geophys. Res. **85**, 4616 (1980).

[17]M. Rusbridge, Plasma Phys. **13**, 977 (1971), and **19**, 1087 (1977).

[18]T. Sato, H. Matsumoto, and K. Nagai, J. Geophys. Res. **87**, 6089 (1982).

[19]D. Fyfe and D. C. Montgomery, J. Plasma Phys. **16**, 181 (1976).