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Breakup of the electron current layer during 3-D collisionless magnetic reconnection

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Abstract. The structure of the electron current layer which forms in the dissipation region during magnetic reconnection in a collisionless plasma is explored by advancing the $3-D$ electron magnetohydrodynamic (EMHD) equations. The current layer thins down below the electron skin depth c/ω_{pe} and then breaks up into a fully turbulent distribution of swirling vortices. The turbulence is sufficiently strong that current is largely shunted into the plane of the magnetic reconnection. The results are consistent with the absense of electron scale current layers in satellite observations of the magnetosphere.

Introduction

Magnetic reconnection plays an important role in the dynamics of the magnetosphere, the solar atmosphere and in laboratory fusion experiments. In the magnetosphere, where the classical resistivity is essentially zero, electron inertia enables the frozen flux constraint to be broken and reconnection to proceed [*Vasyliunas,* 1975,]. Reconnection takes place in a narrow region around an X-point of the magnetic configuration, the dissipation region. It has recently been demonstrated that in a $2-D$ model of collisionless reconnection, the dissipation region develops a two-scale structure consisting of a narrow layer of electron current of scale length $\delta_e = c/\omega_{pe}$ embedded in a broader current layer controlled by the ion dynamics [*Biskamp et al.,* 1995, ; *Shay et al.,* 1997,]. It has also been suggested that in $3-D$ such narrow electron current layers would be strongly unstable to sheared flow instabilities [*Drake et al.,* 1994,]. Hybrid simulations with particle ions and fluid finite mass electrons have confirmed that isolated thin current layers develop into a turbulent filamentary state [*Drake and Denton,* 1996,]. We present evidence from $3-D$ simulations of collisionless magnetic reconnection that the narrow electron current layers which form self-consistently in the dissipation region break up and become fully turbulent. Unlike the case of the isolated current layer studied previously [*Drake et al.,* 1994,], the turbulence is sufficiently strong that it is problematic to even define a current layer, the current being largely shunted into the plane of the reconnection process.

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Ohm's Law and the Electron Magnetohydrodynamic Equations

In a two fluid description of collisionless reconnection, the Ohm's law is given by the electron momentum equation

$$\frac{4\pi}{\omega_{pe}^2}\frac{d\mathbf{j}}{dt} = \mathbf{E} + \frac{1}{c}\mathbf{v}_i \times \mathbf{B} - \frac{1}{nec}\mathbf{j}\times\mathbf{B} + \frac{1}{ne}\nabla p_e, \tag{1}$$

where we have written the electron velocity in terms of the ion velocity $\mathbf{v}_i$ and the current $\mathbf{j}$, neglected the ion velocity in the inertia term and for simplicity taken the electron pressure p_e to be isotropic [*Hesse and Winske,* 1993,]. The inertia term brings in the scale length δ_e into the problem and the Hall term $\mathbf{j}\times\mathbf{B}$ the scale length $\delta_i = c/\omega_{pi}$. The two-scale structure of the dissipation region [*Biskamp et al.,* 1995, ; *Shay et al.,* 1997,] arises because the electrons and ions decouple on scale lengths smaller than the ion inertial length δ_i [*Kinsep et al.,* 1990, ; *Bulanov et al.,* 1992, ; *Mandt et al.,* 1994,], where the Hall term dominates the usual $\mathbf{v}_i\times\mathbf{B}$ term. When the plasma flowing toward the neutral line approaches within a distance δ_i of the neutral line the ions are diverted in the direction of the outflow while the electrons, being frozen into the magnetic field, move with increasing velocity toward the neutral line. At distances of the order of δ_e from the neutral line they become demagnetized and are accelerated toward the outflow where they merge back with the ion flow. To describe the dynamics of the electron current layer, the goal of this paper, the ion motion can be neglected since the scale lengths involved are smaller than δ_i. Solving (1) for $\mathbf{E}$ and inserting the result into Faraday's law yields the electron magnetohydrodynamic (EMHD) equations [*Kinsep et al.,* 1990, ; *Bulanov et al.,* 1992, ; *Drake et al.,* 1994,],

$$\frac{\partial\hat{\mathbf{B}}}{\partial t} + \nabla\times(\mathbf{j}\times\hat{\mathbf{B}}) = -\mu\nabla^6\mathbf{B}, \tag{2}$$

where

$$\hat{\mathbf{B}} = \mathbf{B} - \delta_e^2\nabla^2\mathbf{B} \tag{3}$$

and

$$\mathbf{j} = \nabla\times\mathbf{B}. \tag{4}$$

The time and space scales and field strength have been normalized to the whistler time $L^2/\delta_e^2\Omega_e$, length L, and magnetic field B_0, with $\Omega_e = eB_0/m_ec$ the electron cyclotron frequency. Note that Eqn.(4) implies that the electron motion is imcompressible in the EMHD limit. We have also introduced a generalized dissipation rate μ which allows us to control the energy at the grid scale in the numerical calculations.

In conventional MHD the Alfvén wave drives magnetic reconnection as the bent magnetic field in the outflow region straightens out. In the case of EMHD the whistler wave drives reconnection. The detailed mechanism, which involves the development of the out-of-plane component of $\mathbf{B}$ was discussed in detail previously [*Mandt et al.,* 1994,]. The structure of the electron current layer which develops around the neutral line was analyzed for the $2-D$ system [*Biskamp et al.,* 1995,]. The current layer is elongated with a width in the inflow direction given by δ_e and a length in the outflow direction which scales as $\delta_e^{2/3}$. Thus, unlike the case of resistive MHD [*Biskamp,* 1986,] the current layer remains microscopic, that is, it does not elongate to the macroscale in the outflow direction. In addition, the reconnection rate is independent of δ_e so that the electron layer does not control the rate of reconnection. Nevertheless, the structure of the electron current layer remains important since data from satellites [*Russell and Elphic,* 1979,] as well as from laboratory experiments [*Gekelman and Stenzel,* 1984, ; *Yamada et al.,* 1996,] do not support the existence of such narrow layers.

Results of Simulations

We study the merging of two isolated, circular flux bundles in a $3-D$ system as described by the EMHD equations (2). The flux bundles are initialized in the $x-y$ plane on the diagonal of a square box of edge length 2π. In the initial state the magnetic field from each flux bundle is calculated from $\mathbf{B} = \nabla z \times \nabla \psi$ with the magnetic flux function ψ,

$$\psi \sim e^{-r^4/r_0^4}$$

with r the distance from the center of the bundle and r_0 the characteristic radius. The rapid fall-off of the flux for $r \gg r_0$ implies that the bundles carry zero net current and therefore do not, in principle, interact with each other or the boundaries in the initial state. In the actual calculations the bundles are placed so that they overlap slightly. The small amount of magnetic flux linking both bundles causes them to attract. The peak poloidal magnetic field in each bundle is unity. A uniform out-of-plane magnetic field B_{z0} as well as small amplitude random perturbations are also added to the initial state. This configuration has the advantage that magnetic reconnection commences quickly and proceeds vigorously until the two flux bundles merge completely, independent of boundary conditions. The associated current layer forms rapidly, facilitating the exploration of its stability. The calculations have been completed with two independently constructed codes, one which uses a conventional pseudo-spectral method and a second which advances the equations in configuration space. The results from the two codes are indistinguishable. The number of modes is chosen to provide adequate spatial resolution, varying from $256 \times 256 \times 32$ to $512 \times 512 \times 64$. In all cases the same minimum scale length of the grid is chosen in each of the spatial directions. The physical length of the box in the z direction is typically much smaller than that in the transverse directions, which is appropriate because the instabilities which control the breakup of the current layer have scale lengths which are several times the width of the current layer, which is comparable to δ_e and much smaller than the overall size of the bundles.

In Fig. 1a a blow-up of the out-of-plane current j_z in the $x-y$ plane is shown at $t = 1.0$ from a simulation on a grid of $512 \times 512 \times 32$ with $\delta_e = 0.2$, $B_{z0} = 0.0$ and $\mu = 2.0 \times 10^{-9}$. At this time a well-developed current layer (black) has formed around the neutral line in the center of the figure. In Figs. 2a and 3a vector plots of the electron flow velocity at the same time are shown in planes cut through the positive (perpendicular to the current layer) and negative (parallel to the current layer) diagonals of Fig. 1a, respectively. In the cut perpendicular to the current layer in Fig. 2a, the strong upward flow in the center of the figure is the current sheet. At this time it has developed a slight, z-dependent wobble. The plasma on either side of the current sheet is flowing toward the current sheet. The downward flow outside

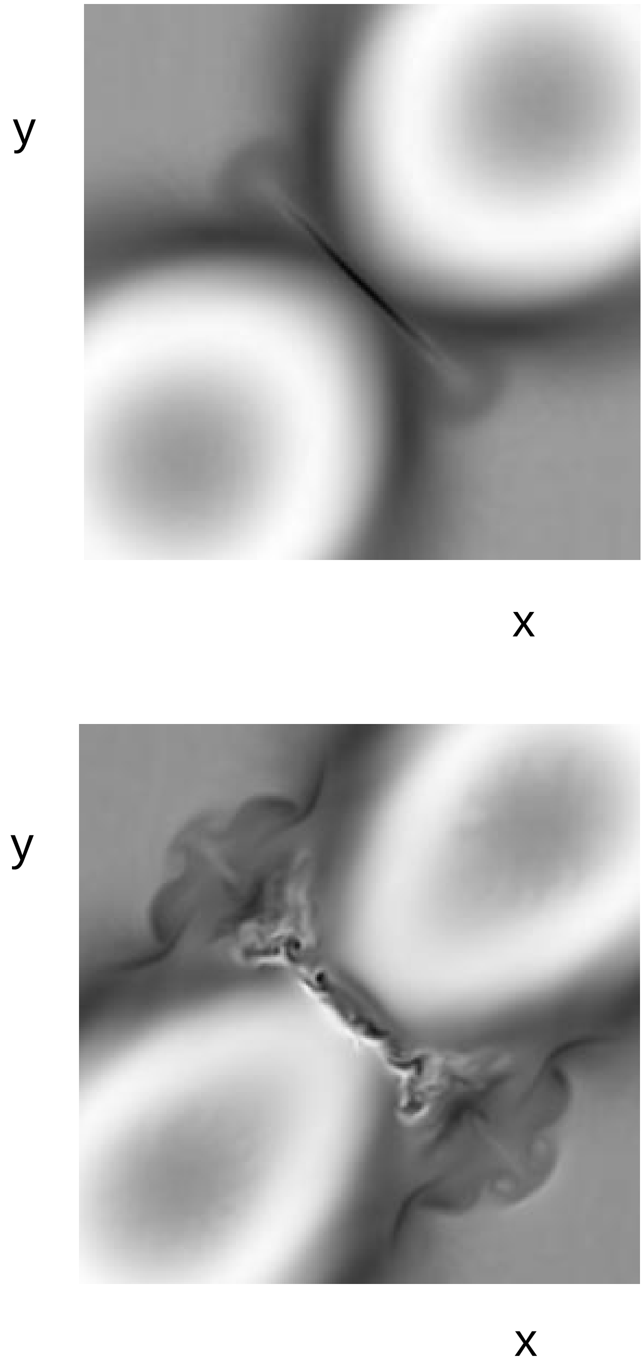

Figure 1. Greyscale plot of the axial current j_z in a $\pi \times \pi$ region of the $x-y$ plane at $t = 1.0$ in (a) and $t = 1.75$ in (b). Note that the current layer is a region of negative current.

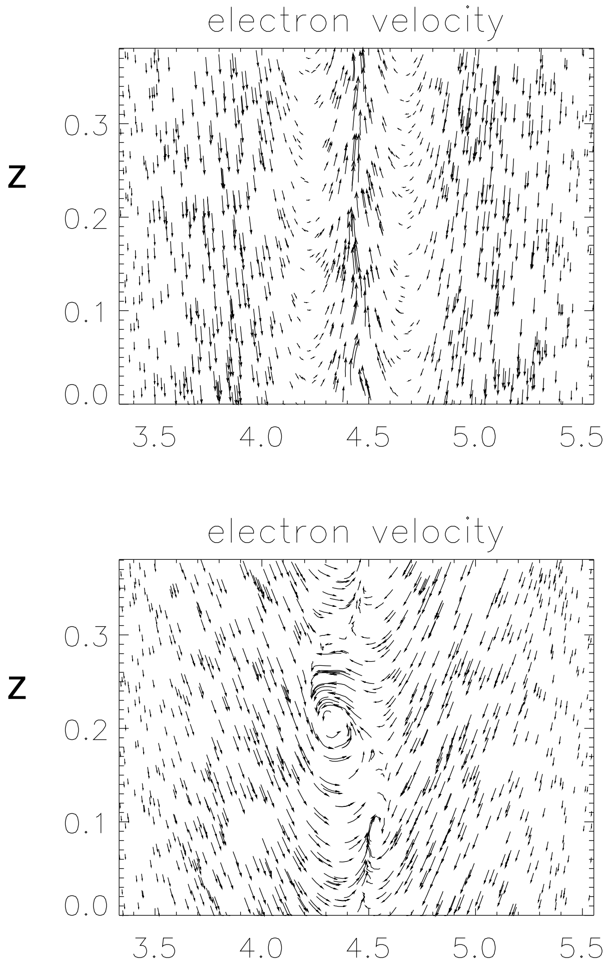

Figure 2. Electron flow velocity in a plane cutting across the current layer at $t = 1.0$ in (a) and $t = 1.75$ in (b). The horizontal axis is along the positive diagonal (x=y) of Fig. 1. In (a) the current layer corresponds to the region of upward flow (downward current) in the middle of the figure.

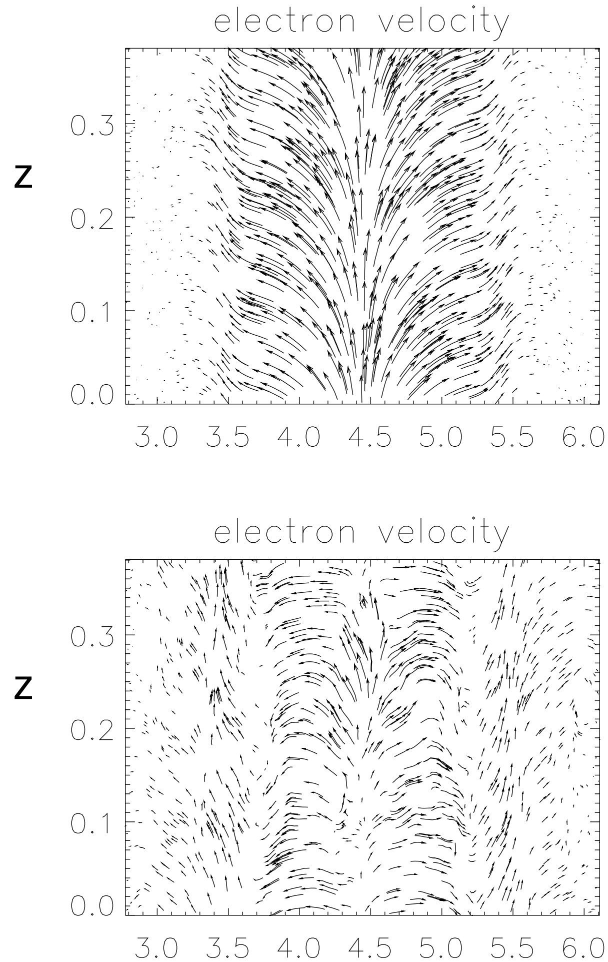

Figure 3. Electron flow velocity in the plane of the current layer at $t = 1.0$ in (a) and $t = 2.0$ in (b). The horizontal axis is along the negative diagonal ($y = 2\pi - x$) of Fig. 1.

of the current sheet is associated with the current in the initial equilibrium. In the plane of the current sheet in Fig. 3a the neutral line is along a vertical line in the center of the plot. The electrons are flowing vertically upwards along the neutral line but then turn outward in the direction of the outflow on either side of the neutral line. This plot illustrates the mechanism which ejects the electrons which have been accelerated to high velocity by the reconnection electric field near the neutral line. The reconnected magnetic field points out of the page to the left of the neutral line and into the page to the right. The Lorentz force from this magnetic field causes the electrons to turn away from the neutral line. Thus, the outflow velocity of the electrons from the neutral line is equal to the velocity resulting from the acceleration by the reconnection electric field. The scale size of the current layer is simply the Larmor radius based on this velocity and the strength of the reconnected magnetic field in the outflow region.

In Figs. 1b, 2b, and 3b we show corresponding plots at later times. In the plot of j_z in the $x-y$ plane at $t = 1.75$ in Fig. 1b the current layer consists of a complex mix of positive and negative values which extend over a much broader region than in Fig. 1a, indicating that the current layer has broken up. The white areas are regions where the current is flowing in the opposite direction to the original current, which can be seen more clearly in the vector plots of the electron flow. Transverse to the current layer in Fig. 2b at $t = 1.75$ there is now a very strong flow toward the neutral line since the reconnection rate has increased substantially since the earlier plot in Fig. 2a. However, it is essentially impossible to even identify a current layer such as that in Fig. 2a. There is a remnant of the layer at the top and bottom of the figure but the large vortex in the center of the figure has disrupted the upward electron flow. The upward and downward flows in the vortex produce the parallel regions of positive and negative current seen in Fig. 1b. Similar behavior can also be seen in the electron velocity vectors in the plane of the current layer shown in Fig. 3b at $t = 2.0$. Near the bottom of the figure the upward flow of electrons has essentially been diverted into the $x-y$ plane, while further upward the upward flow continues.

Discussion

The stability of an isolated electron current layer has been discussed earlier [*Drake et al.,* 1994,]. The $3-D$ flows which are present in the present simulations are more complex than in this previous model. Nevertheless, this simpler case provides a useful framework for discussing the results of the present simulations. The current layer shown in Fig. 1a, prior to the breakup, has a scale size which is smaller than δ_e. For scale lengths of this order, the inertial term in Ohm's law in (1) dominates over the remaining terms and to lowest order is simply given by

$$\partial \mathbf{v}_e/\partial t + \mathbf{v}_e \cdot \nabla \mathbf{v}_e = 0, \tag{5}$$

which is identical to the equation of motion of a neutral fluid. Electron current layers of scale length of order or smaller than δ_e are therefore unstable to the classic Kelvin-Helmholtz instability [*Drake et al.,* 1994, ; *Biskamp et al.,* 1996,] and it is this instability which underlies the breakup of the layer seen in Figs. 1-3.

It might have been expected that breakup of the current sheet would result in a strongly enhanced rate of magnetic reconnection. That is not the case, however, because the electron current layer, even prior to the breakup, does not control the rate of reconnection [*Biskamp et al.,* 1995, ; *Shay et al.,* 1997,]. Electron inertia is required to break the usual frozen flux constraint. Nevertheless, the amount of current carried in the layer is sufficiently small that it does not slow the rate of reconnection and therefore it should not be surprising that the rate of reconnection does not go up as the layer breaks up. What is seen is an approximately fourfold increase in the rate of dissipation of energy in the system. In the absense of turbulence most of the decrease of the magnetic energy goes into the kinetic energy of the electrons in the form of high speed flows. When current layer breaks up, this high speed flow energy is rapidly transfered to short scale and is dissipated. The rate of energy dissipation is, however, independent of the dissipation rate μ, as was found earlier in $2-D$ simulations of EMHD turbulence [*Biskamp et al.,* 1996,]. In the real physical system this energy, which is nothing more that random electron motion, would appear as electron thermal energy.

Simulations have also been carried out for a range of values of the axial magnetic field B_{z0} up to 3.0. The breakup of the current layer persists until $B_{z0} \sim 2$ but becomes much weaker at higher values. However, it is premature at this point to conclude that the current layers are completely stabilized by a large axial magnetic field. The reconnection of the flux bundles is complete after about three whistler time units. Thus, instabilities with growth times exceeding this time scale do not have time to grow to finite amplitude. The linear growth rate of current-gradient-driven whistlers decreases with the strength of the axial magnetic field but remains positive [*Drake et al.,* 1994,].

Conclusions

Electron current layers of scale length c/ω_{pe} which form in the dissipation region in 2-D models of collisionless magnetic reconnection break up as a result of shear-flow instability in a 3-D system. On the basis of earlier simulations of isolated current layers (not produced self-consistently as a result of magnetic reconnection) [*Drake and Denton,* 1996,], it had been expected that this shear-driven turbulence would simply broaden the electron current layer and that the electrons would remain a major carrier of the current in the dissipation region. However, the present simulatations call into question this assumption. The breakup of the self-consistent current layer is much stronger, with the electron current largely being shunted into the plane of the reconnection. It is, of course, possible that some of the current in the layer could also be shunted to the ions. Since the ion motion has been neglected in the present simulations, this possibility can not be ruled out and should be explored in a more complete model with the full ion dynamics.

The breakup of the electron current layer seen in the present simulations is a major step forward in trying to understand the absense of such narrow layers in laboratory [*Gekelman and Stenzel,* 1984, ; *Yamada et al.,* 1996,] and satellite [*Russell and Elphic,* 1979,] observations. In addition, it is becoming increasingly clear that reconnection in collisionless plasma is not laminar and that the dissipation region and probably the entire outflow region should exhibit turbulence with frequencies up the electron cyclotron frequency.

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