Full Particle Simulations of Collisionless Magnetic Reconnection

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The investigation of collisionless magnetic reconnection in the magnetosphere by means of full particle simulations constitutes a grand challenge problem in computational physics. A wide range of spatial and temporal scales must be treated, and the local reconnection region is strongly influenced by processes occurring on a macroscopic scale. Recent progress in the area is reviewed, including the problem of externally-driven magnetic reconnection in the presence of a normal magnetic field component.

1. Introduction

Magnetic reconnection plays a fundamental role in the dynamics of the magnetosphere. It facilitates the entry of particles and energy from the solar wind into the magnetosphere at the magnetopause and allows the internal magnetospheric topology to change. Magnetic reconnection relies on the presence of a dissipation mechanism in a localized region of space, the so-called diffusion region. In a sufficiently collisional plasma, resistive MHD is valid for describing this region. In the magnetosphere, however, the classical collision rate is very small, and one must consider the collisionless description of reconnection. Here the dissipation region is governed by the generalized Ohm’s law [e.g., Drake, 1995], which introduces new physics associated with the Hall term, electron pressure gradient effects, and electron inertia terms.

Full particle simulation of collisionless reconnection relevant to magnetospheric configurations represents a true grand challenge problem in computational physics. The simulations must be at least 2-D ($x, y$ in magnetospheric coordinates). The reconnection physics evolves on ion temporal scales (the gyrofrequency $\Omega_i$) and a wide variety of spatial scales, ranging from electron scales ($c/\omega_{pe}$ and $\rho_e$) through ion scales ($c/\omega_{pi}$ and $\rho_i$) to macroscopic scales. An explicit particle simulation must resolve the very shortest spatial and temporal scales, and thus the cost of a 3-D explicit particle simulation must resolve the very shortest spatial and temporal scales, ranging from electron scales ($c/\omega_{pe}$ and $\rho_e$) through ion scales ($c/\omega_{pi}$ and $\rho_i$) to macroscopic scales. An explicit particle simulation must resolve the very shortest spatial and temporal scales, and thus the cost of a 3-D explicit particle simulation which extends through the ion scales varies like $(m_i/m_e)^{5/2}$ [Pritchett, 2000]. Finally, the usual simulations of reconnection in a simple current sheet need to be embedded into a realistic open configuration in which particles and magnetic flux can both enter into and escape from the local reconnection region.

In section 2 we briefly summarize a number of issues concerning collisionless reconnection that have been investigated in the past few years using full particle simulations. In section 3 we discuss in more detail the onset problem for externally driven reconnection in the presence of a finite normal magnetic field component.

2. Current Issues in Reconnection Simulations

2.1 Nature of the Simulation

Traditionally, particle simulations are of the initial value type where the desired physics is allowed to evolve out of the noise present in the initial configuration. This approach has some drawbacks for studies of reconnection: the reconnection physics can take a long time to establish itself, and the linear stage can be quite sensitive to the details of the dissipation mechanism. The Geospace Environment Modeling (GEM) prescription [Birn et al., 2001] involved imposing a large amplitude magnetic island perturbation to trigger the reconnection dynamics. This permitted a comparison between different types of simulation models (Hall MHD, two fluid, hybrid, and full particle) and identified the Hall term as a common mechanism that permits fast reconnection. However, the perturbation $B_i$ results in a $J_B B_z/e$ stress along the current sheet directed away from the $X$ line which is not compensated by any pressure difference [Pritchett and Coroniti, 2004]. Thus the reconnection is actually driven internally in response to the order-unity stress imbalance. An alternative driving procedure is to apply an external convective electric field at the $z$ boundaries [Horiuchi and Sato, 1994; Pritchett, 2001b]. This allows the simulation to determine a self-consistent response to the perturbation.

2.2 Saturation of the Tearing Instability

The tearing instability in a Harris [1962] neutral sheet occurs at relatively long wavelengths, $0 < k_s w < 1$, where $w$ is the half thickness of the current sheet. Karimabadi et al. [2004b] showed from 2-D simulations with $\rho_i/w = 1$ that single-island tearing (only one unstable mode) saturates at very small amplitudes (island size $\ll w$) due to preferential electron heating in the parallel direction. A value of $T_e \perp /T_e \parallel \approx 0.95$ is sufficient to shift the marginal stability point below $k_s w = 0.5$. The presence of multiple unstable modes (obtained by enlarging the system size) allows the system to get past the stabilization and grow to ion scales. Similarly, Tanaka et al. [2004] found that single-island tearing saturates at a low level provided that $w > 3.5c/\omega_{pe} \approx 0.3c/\omega_{pe}$ for $m_i/m_e \sim 100–200$.

2.3 Effect of a Guide Field

The presence of an appreciable zero-order out-of-plane ($B_g$) component of the magnetic field is one of the characteristic features of dayside reconnection. Simulations of the GEM type showed that the reconnection rate is only slightly reduced for $B_{0z}/B_0 < 1$ [Pritchett, 2001a; Pritchett and Coroniti, 2004; Ricci et al., 2004a; Hesse et al., 2004]. The detailed properties of the fields and particles in the diffusion region, however, are strongly altered. The reconnection electric field $E_R$ near the $X$ line is supported by both quasi-viscous and bulk inertia processes [Hesse et al., 2004;
Ricci et al., 2004a]. As has been analyzed by Rogers et al. [2001], the guide field dynamics is dominated by the kinetic Alfvén wave. A characteristic signature of this dynamics is the formation of a density asymmetry across the center of the island. This asymmetry is manifested in the formation of a deep density cavity along one pair of separatrix arms [Matsumoto et al., 2004; Cattell et al., 2005]. In these cavities, a parallel electric field accelerates the electrons to form beam features with peak speed \( > v_{AE} \), where \( v_{AE} \) is the electron Alfvén speed based on \( B_0 \) and the peak density \( n_0 \). The large drift of the electron beam relative to the ions leads to the excitation of Buneman-like structures within the parallel electric field region.

### 2.4 Kinetic Signatures of Reconnection

It is by now well known that the Hall currents produce a perturbed quadrupolar out-of-plane \( B_y \) component during reconnection [Sonnerup, 1979; Terasawa, 1983]. Additionally, ion FLR effects also contribute [Karimabadi et al., 2004a]. Numerous spacecraft observations have identified some or all of this structure. With a significant zero-order guide field, however, this simple pattern is distorted [Rogers et al., 2003; Pritchett and Coroniti, 2004].

The density cavities associated with guide field reconnection have been shown to contain electron holes [Drake et al., 2003; Cattell et al., 2005]. Observations of such holes in association with reconnection have been made by Polar at the magnetopause [Cattell et al., 2002], by Wind in the magnetotail [Farrell et al., 2002], and Geotail at the magnetopause [Matsumoto et al., 2003]. Most recently, large amplitude solitary waves, identified as electron holes, have been observed during waveform captures on two of the four Cluster satellites at times corresponding to passage of a magnetotail reconnection \( X \) line [Cattell et al., 2005]. Particle simulations could reproduce the Cluster data only with the addition of a small (\( \sim 0.2B_0 \)) guide field.

Using higher time resolution field measurements on the Polar satellite, Mozer et al. [2004] have observed electric fields with amplitudes up to 140 mV/m and \( \leq 10 \) msec duration at the magnetospheric side of the dayside magnetopause. These fields are predominantly perpendicular to \( B \), are electrostatic, and occur inside local minima in the plasma density. Initially, it was not possible to determine the spatial scale of the fields. Similar electric field structures have been observed in guide-field simulations [Pritchett, 2005b]. Here the fields occurred around the island perimeter and had a half width of about three times the local Debye length in the density cavity.

Wind observations in the magnetotail [Oieroset et al., 2002] provided direct evidence of energetic electrons up to \( \sim 300 \) keV in the magnetic reconnection diffusion region of the magnetotail. Particle simulations of driven reconnection [Pritchett, 2005a] have shown that such relativistic electrons can be produced by direct acceleration (Landau interaction) of electrons with \( v_{\perp} \approx 0 \) at the \( X \) line.

### 2.5 3-D Effects in Reconnection

The basic reconnection process in a simple current sheet is 2-D. Except when the thickness \( L \) reaches \( c/\omega_{pi} \) scales, the 2-D reconnection rate is too slow to explain substorm onset. A number of simulation investigations have shown that the reconnection rate is greatly augmented in a full 3-D system [Scholer et al., 2003; Silin and Bührner, 2003; Shinohara and Fujimoto, 2004; Ricci et al., 2004b]. This effect is due to the influence of the lower hybrid drift instability (LHDI) which requires a finite \( k_y \) wavevector for excitation. The nonlinear evolution of the LHDI causes anisotropic heating of the electrons (\( T_{e\perp}/T_{e\parallel} > 1 \)) and thins the current sheet with an accompanying increase in the peak current density. Both effects enhance the growth rate of the tearing instability. Whether these effects will persist in the presence of a background density component, a guide field, and/or a normal field component is not yet clear.

### 3. Externally Driven Magnetic Reconnection

#### 3.1 The Role of the Normal Field

The question of whether the collisionless tearing instability can be excited in a plasma sheet configuration with a finite normal magnetic field component has been a controversial topic in magnetospheric physics for nearly 40 years. The presence of such a normal field removes the Landau resonance between particle and field if the gyrofrequency is greater than the tearing growth rate [Schindler, 1974; Galeev and Zelenyi, 1976]. Further, the tearing mode electromagnetic field produces a strong compression of the electron density which is independent of \( T_e \) [Lembège and Pellat, 1981]. This perturbation forces a large electrostatic potential in order to maintain charge neutrality. The energy associated with the electron compression generally exceeds the free energy available from the reversed magnetic field configuration.

The consensus of a number of investigations is that the spontaneous ion tearing instability cannot exist in the transition region between dipole and tail fields where significant disruptions associated with substorm onset occur [Pellat et al., 1991; Brittnacher et al., 1994, 1998]. The situation further down the tail is less clear [Stinov et al., 2002].

It is by no means clear that the spontaneous tearing instability is the relevant process for explaining substorm onset in the magnetotail. Statistical evidence suggests that a substantial fraction (\( \sim 60\%) \) of substorm onsets can be associated with northward turnings of the IMF [Hsu and McPherron, 2003]. Prior to onset, a southward IMF imposes an enhanced convection electric field on the magnetotail. In the present paper we revisit the question of how such an electric field can trigger reconnection in a model plasma sheet configuration containing a finite normal field component [Pritchett, 2005a].

#### 3.2 Simulation Model

We use a 3-D electromagnetic full particle code with an explicit time advance and Poisson correction for the electric field. The initial configuration is based on the Lembège and Pellat [1982] quasiparabolic equilibrium with a normal field strength \( B_n/B_0 = 0.04 \) at the center of the current sheet. There is a 20\% non-drifting background plasma component. The driving field is applied at the \( z \) boundaries and is localized in \( x \) near the center of the system. The field strength is \( cE_{0y}/v_A B_0 = 0.2 \). The system dimensions are \( L_x \times L_y \times L_z = 25.6\pi/c/\omega_{pi} \times 12.8\pi/c/\omega_{pi} \times 12.8\pi/c/\omega_{pi}. \) The

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**References**


Fig. 1. Time histories of \( \psi \) (a) the reconnecting flux \( \psi \) computed from the perturbed potential \( \delta A_y(x, z = 0) \). Figure 1a shows the time history of \( \psi \). There is a relatively long development period of \( \Omega_0 t \sim 20 \) during which \( \psi \) grows slowly as the perturbation fields propagate in from the boundary. As shown in Figure 1b, the width of the current layer decreases during this period from \( 1.6c/\omega_{pi} \) down to a minimum of \( 0.4c/\omega_{pi} \). Subsequently, the value of \( \psi \) increases much more rapidly, with the peak slope at \( \Omega_0 t \sim 35 \) corresponding to a reconnection field \( cE_y/v_A B_0 \approx 0.44 \). The thinning of the overall current layer is the result of the formation of an embedded electron current layer.

The rapid reconnection phase is initiated after the \( B_z(x, 0) \) profile is driven through zero at \( \Omega_0 t \approx 21 \) near \( x \approx 2c/\omega_{pi} \).


