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Fully Kinetic Simulations of Slow-Mode Shocks

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Abstract. Much of the theoretical understanding concerning the structure and essential properties of the slow-mode shock has been obtained from extensive hybrid calculations in which a full kinetic description is retained for the ions while the electrons are approximated as a massless adiabatic fluid. Due to the relatively broad spatial and relatively slow temporal scales of the slow shock, one would expect this approximation to be well justified. However, implicit simulations with kinetic electrons have produced significant differences in comparison to standard hybrid results. In this work, we re-examine the importance of electron dynamics to the slow shock using one-dimensional fully kinetic simulations. We employ a simple explicit simulation technique and fully resolve all relevant spatial and temporal electron scales. The resulting shock structure and ion heating are in excellent agreement with hybrid simulations, indicating the total dissipation arising from kinetic electrons is relatively minor. However, the electron heating is somewhat larger than the corresponding hybrid simulation and clear non-Maxwellian features are observed. In the upstream region, back streaming electrons give rise to double peaked distributions while in the downstream region bi-Maxwellian distributions are observed with $T_{e\|} > T_{e\perp}$.

1 Introduction

In magnetohydrodynamic (MHD) theory, slow magnetosonic shocks occur for upstream flow velocities greater than the slow magnetosonic speed but less than or equal to the intermediate speed, $V_A \cos(\theta_n)$, where V_A is the Alfvén velocity and θ_n is the shock normal angle. When the upstream flow velocity is equal to the intermediate speed, the transverse component of the downstream magnetic field will vanish, producing a switch-off shock. In contrast to fast shocks which convert flow energy into thermal and field energy, slow shocks convert magnetic energy to plasma kinetic energy. Thus, the slow-mode shock is hypothesized to play an important role in steady state reconnection (*Petscheck*, 1964).

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Current theoretical understanding of the slow-mode shock is derived from the two-fluid theory of *Coroniti* (1971) together with extensive small-scale hybrid simulations of the shock transition (*Swift*, 1983; *Winske et al.*, 1985; *Omidi and Winske*, 1992, 1989). In addition to these small-scale simulations, large-scale hybrid simulations have been carried out which encompass a significant fraction of the magnetotail (*Krauss-Varban and Omidi*, 1995; *Lottermoser et al.*, 1998), thus allowing shock transitions to form more naturally as part of the reconnection process. In these large-scale simulations, the observed transition layers do not always conform exactly to the expected properties of slow shocks (*Krauss-Varban and Omidi*, 1995). Nevertheless, a fairly consistent picture has emerged concerning the structure and essential properties of the slow shock. In the hybrid simulations, the observed shock transitions are of the order 5 - 10 ion inertia lengths (c/ω_{pi}), with relevant time scales on the order of the ion gyro-period. For these spatial and temporal scales, one would expect the assumption of adiabatic fluid electrons to be quite reasonable.

However, recent simulation results with kinetic electrons (*Brackbill and Vu*, 1993) have called into question the validity of the electron fluid approximation. These simulations retain a kinetic description for both ions and electrons by solving an implicit formulation of the dynamical equations. Using this sophisticated technique, one can model plasma behavior on the ion time scale without having to resolve the much faster electron time scale or the much smaller electron length scale (*Vu and Brackbill*, 1992). For the slow shock problem, this fully implicit kinetic approach predicts a more equal sharing (between ions and electrons) of the shock-induced heating. This results in a significantly lower downstream ion temperature than predicted by hybrid codes and greater electron energy transport from downstream to upstream. The authors attribute these results to electron kinetic processes, but do not offer any specific mechanisms.

In an effort to confirm this puzzling result, we re-examine the slow-mode shock using one-dimensional fully kinetic simulations. In contrast to *Brackbill and Vu* (1993), we employ a simple explicit simulation technique and fully resolve all relevant spatial and temporal electron scales. Although this tour de force approach is computationally difficult, the necessary algorithms are strikingly simple. Unfortunately, results obtained from these explicit simulations do not support the previous findings. Our full particle simulations are in excellent agreement with hybrid results for the shock structure and ion heating. The primary difference is a relatively small amount of electron heating observed in the full particle simulations.

2 Simulation Method

We have extended the previous 1D hybrid code of *Winske and Omidi* (1993) to a full particle code using a well known explicit electromagnetic algorithm (*Morse and Nielson*, 1971; *Nielson and Lindman*, 1972; *Forslund*, 1985). In this full-Maxwell approach, the fields are calculated using the scalar and vector potentials. Working in the Coulomb gauge, the scalar potential is computed directly from Poisson's equation while the vector potential is advanced in time using an algorithm which allows the time step Δt to exceed the Courant limit (*Nielson and Lindman*, 1972). Intuitively, this corresponds to an implicit treatment of light waves while the rest of the algorithm remains explicit. We have carefully benchmarked this algorithm against the standard explicit approach with a time step much smaller than the Courant condition. Aside from the field solver, the rest of algorithms are nearly identical to the original hybrid code(*Winske and Omidi*, 1993). The particle trajectories are advanced using the leap-frog technique and particle moments are accumulated on the grid with linear interpolation.

In the present study, shocks are formed by reflecting an initially uniform flow off a stationary wall. This is the same approach employed in the previous implicit simulations (*Brackbill and Vu*, 1993). The simulations are carried out in the reference frame of the wall. Thus, a shock is formed near the wall and propagates upstream. The initial plasma parameters and magnetic field are set to produce a switch-off shock as predicted by the Rankine-Hugoniot conditions for Maxwellian distributions (*Tidman and Krall*, 1971). A flux of Maxwellian electrons and ions is injected at the upstream boundary using using the method described by *Cartwright et al.* (2000). Particles hitting the wall are perfectly reflected while particles leaving the inlet are lost from the system. For the inlet boundary condition, the magnetic flux is prescribed and the electrostatic potential is zero. For the wall boundary condition, the electrostatic field and transverse component of the magnetic field are set to zero, consistent with a switch-off shock and global charge neutrality.

In order to allow adequate distance for the slow shock to form and propagate back upstream, we have chosen a box size $L = 80\ c/\omega_{pi}$. To avoid the extreme difference between electron and ion time scales, we employ an artificial electron mass $m_i/m_e = 25$. This is the same value used in the previous implicit simulations (*Brackbill and Vu*, 1993). The ratio of the electron plasma frequency to electron cyclotron frequency was chosen as $\omega_{pe}/\Omega_{ce} = 5$ so that $\omega_{pi}/\Omega_{ci} = 25$ for the chosen mass ratio. To avoid the well-known finite grid instability (*Lindman*, 1970; *Langdon*, 1970), we set the grid spacing equal to the electron Debye length $\Delta x \approx \lambda_d$. For the chosen electron temperature, $\beta_e \equiv 8\pi n T_e/B_o^2 = 0.1$, this requires $N = 6000$ cells. To sufficiently reduce the inherent noise, both ions and electrons are represented by 250 simulation particles per cell resulting in 3×10^6 particles for the system. As mentioned previously, the field solver is stable for time steps exceeding the Courant condition. Thus, we have chosen a time step which slightly exceeds the Courant condition $\omega_{pe}\Delta t = 0.067$ and accurately resolves the electron trajectories ($\Omega_{ce}\Delta t = 0.013$). For a shock normal angle of $\theta_n = 75°$, the Rankine-Hugoniot condition for a switch-off shock requires an upstream flow speed $V_{flow} = \cos(75°)\ V_A$ in the frame of the shock or $V_{flow} = 0.128\ V_A$ in the frame of the wall. All plasma and simulation parameters are summarized in Table I.

The primary difference between the plasma parameters in Table I and those of *Brackbill and Vu* (1993), is that our simulations are for higher temperature $\beta_e = \beta_i = 0.1$ than the previous results where $\beta_e = \beta_i = 0.01$. Since we must require the cell size to be comparable to an electron Debye length, this reduces the numerical difficulty involved in our simulations. Although there is no reason to believe that this difference will greatly alter the essential physics, we have also carried out simulations with $\beta_e = 0.04$ with similar results. These values of β_e and β_i are consistent with observations of slow-mode shocks in the geomagnetic tail (*Ho et al.*, 1996).

The comparison hybrid simulations were carried out with the 1D code of *Winske and Omidi* (1993). The system size, physical parameters, and initial conditions are the same as Table 1. In the hybrid approach, it is only necessary to resolve the ion scales. Thus, the domain was divided into 200 cells and a time step was chosen sufficiently small $\Omega_{ci}\Delta t = 0.02$ to accurately resolve the ion motion. The ion distribution was represented by 250 simulation particles per cell. The electrons were approximated as a massless fluid with an adiabatic equation of state ($\gamma = 5/3$).

3 Results

Since we are primarily interested in electron kinetic effects, we have run the simulation long enough for a shock to form and propagate away from the wall. At this point, it is legitimate to make detailed comparisons of the structure.

Table 1. Simulation parameters for slow shock

$m_i/m_e = 25$	$\omega_{pe}/\Omega_{ce} = 5$	$\theta_n = 75°$
$\beta_i = 0.1$	$\beta_e = 0.1$	$\omega_{pe}\Delta t = 0.067$
$L = 400c/\omega_{pe}$	$\Delta x \approx \lambda_d$	250 part/cell
$V_{flow} = 0.128\ V_A$	in wall frame	

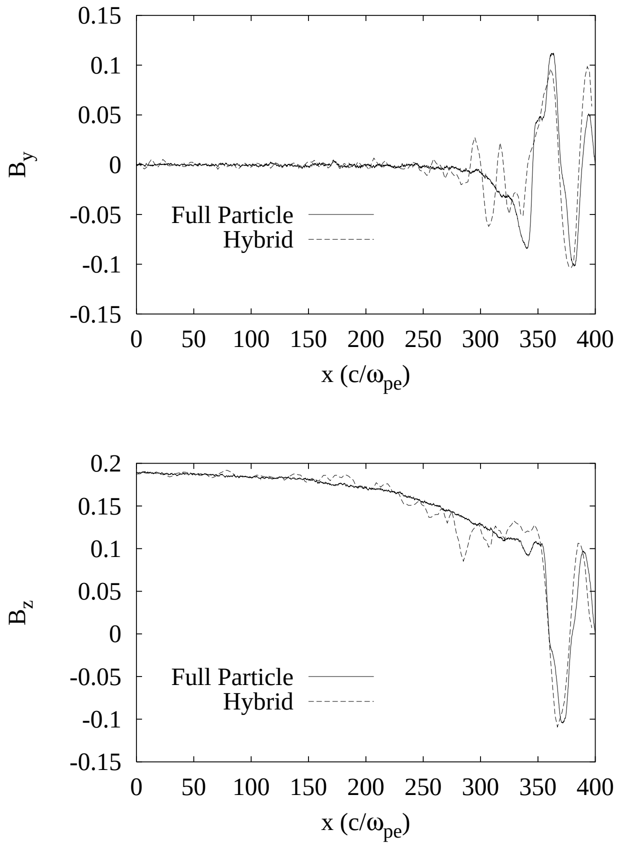

Fig. 1. Comparison of B_y and B_z obtained from full particle simulation with corresponding results from hybrid simulation. The results are at $t\Omega_{ci} = 210$ and for parameters given in Table I.

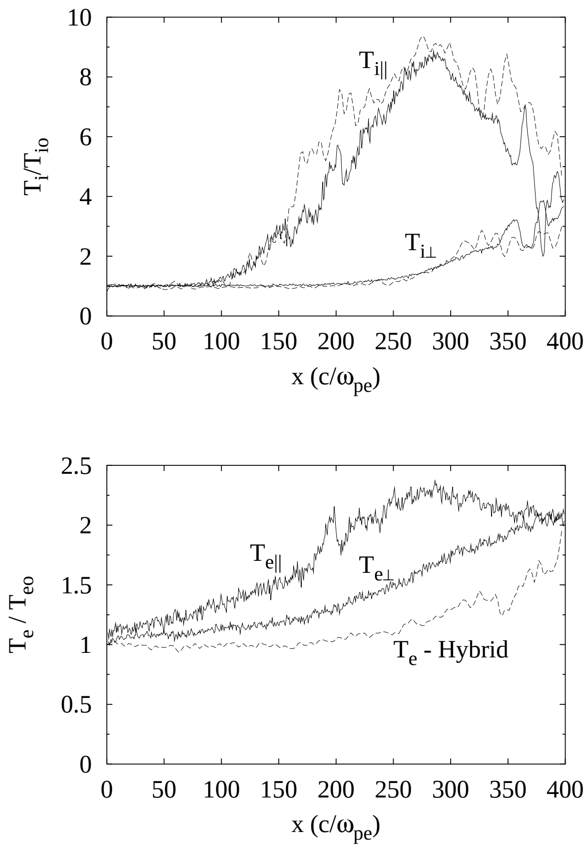

Fig. 2. Comparison of ion (top) and electron (bottom) temperatures obtained from full particle simulation (solid) with corresponding results from hybrid simulation (dashed). The results are at $t\Omega_{ci} = 150$ and for parameters given in Table I. The temperatures are normalized to the initial electron and ion temperatures.

As shown in Figure 1, the magnetic field structure obtained from the full particle simulation is in remarkable agreement with the corresponding hybrid calculation. It is important to note that these results are compared at the same elapsed time $t\Omega_{ci} = 210$, indicating that both the time scale for the shock to form and the shock propagation velocity are in good agreement. In contrast, the previous implicit simulations predict significant differences in both the magnetic shock structure and the shock propagation velocity (*Brackbill and Vu*, 1993).

The electron and ion temperatures resulting from the full particle simulation are compared with a hybrid simulation in Figure 2. In the full particle simulations as well as for the ions in the hybrid simulation, the temperature is computed both parallel and perpendicular to the magnetic field. Considering the inherent noise present in kinetic simulations, the agreement for the ion temperatures is very good. The parallel electron temperature $T_{e\|}$ is 20-80% higher for the full particle simulation than the hybrid T_e result while the perpendicular electron temperature $T_{e\perp}$ is 10-25% larger. The observed increase in $T_{e\|}$ is due primarily to the presence of back streaming electrons and is a bit misleading, since the electron distribution functions in the upstream region are non-Maxwellian in the parallel direction. We are currently working to characterize and understand these non-Maxellian features.

In order to address the issue of numerical heating, we did a comparison run in which the plasma and simulation parameters were identical to Table I, but boundary conditions were changed to a closed periodic system. Obviously, the periodic system is closed and stable, allowing us to easily estimate the energy conservation properties of our algorithm. As expected for an explicit approach, the electrons slowly gain energy. For the long simulation times required in Figure 2, the electron kinetic energy increased approximately 7% while the increase in ion kinetic energy was negligible. For the perpendicular temperature $T_{e\perp}$, this leaves roughly a 15% difference in Figure 2 which may possibly arise from electron kinetic effects. However, in the case of the parallel temperature $T_{e\|}$, it is clear that kinetic effects give rise to a significantly different result. However, these kinetic modifications are sufficiently small that the global structure of the shock is nearly identitcal to the hybrid simulations.

It is also important to note, that the full particle simulations were performed with $m_i/m_e = 25$ which may allow artificial electron kinetic effects to remain in the problem.

To rule out this possibility would require additional simulations at larger mass ratio. These simulations are prohibitive with our current computational resources. Nevertheless, the differences we see between full particle and hybrid are relatively small in comparison to the previous implicit simulations where a factor of two difference in the ion temperature was reported (*Brackbill and Vu*, 1993).

4 Observations

Although the primary focus of this report is oriented toward simulation results, it is important to mention observations relating to electron and ion heating across slow-mode shocks. As noted by *Brackbill and Vu* (1993), ion heating is greater than electron heating in the observations from ISEE 2 of a slow-mode shock in the plasma sheet boundary layer (*Feldman et al.*, 1987). In more recent observations from GEOTAIL, ion and electron upstream and downstream temperatures have been reported for slow shocks (*Saito et al.*, 1995; *Seon et al.*, 1996). These observation indicate the vast majority of heating is associated with the ions. Finally, in a statistical study of 86 slow shock events obtained from distant ISEE 3 geomagnetic tail passes (*Ho et al.*, 1996), it was reported that the average increase in electron density across the shock was ~ 1.7 while the the average increase in electron temperature was ~ 1.8. This electron temperature increase is somewhat larger than a simple adiabatic estimate [$(1.7)^{2/3} \approx 1.4$], but is small in comparison to the ion heating across the shock.

5 Summary and Future Work

We have carried out fully kinetic explicit simulations of a slow-mode switch-off shock. The resulting shock structure and ion heating are in excellent agreement with hybrid simulations. However, we find a small about of additional electron heating (beyond adiabatic), primarily in the parallel direction. Since it is not possible to completely eliminate numerical heating from our algorithm, it is difficult to ascertain the true contribution from electron kinetic effects or how these contributions might scale with m_i/m_e. Nevertheless, we do observe significant non-Maxwellian features in the electron distributions functions, including back streaming electrons in the upstream region and bi-Maxwellian distributions in the downstream region. We are currently working to characterize and understand these non-Maxwellian features.

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