Final Technical Report
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PI: Yu Lin
Auburn University

With the 3-year support of our current DOE grant (currently in the third year), we have developed the new gyrokinetic (GK)-electron and fully-kinetic (FK)-ion scheme, finished its benchmark for a uniform plasma in 1-D, 2-D, and 3-D systems against linear waves obtained from analytical theories, and carried out a further convergence test and benchmark for a 2-D current sheet against tearing mode and other instabilities in linear theories/models. More importantly, we have, *for the first time*, carried out simulation of linear instabilities in a 2-D Harris current sheet with a broad range of guide field and the realistic m_i/m_e. The milestones of our investigation are as planned originally, to finish the scheme benchmark in two years and start the investigation of 2-D Harris sheet in the third year.

In addition, we have begun an effort to develop a 3-D hybrid code for simulation of the SSX reconnection experiment. Initial results related to this proposal are described below.

1. Development and Benchmark of the GKe/FKi Scheme for Uniform Plasmas

The novel new kinetic simulation model, the GKe/FKi model as described briefly in the Introduction, has been developed to investigate dynamics in collisionless plasmas. The simulation scheme has then been successfully benchmarked for linear waves for 1-D, 2-D, and 3-D uniform plasma systems against analytic dispersion relation. The results showed that the linear wave properties obtained from the numerical results agree very well with those from the theoretical analysis of the whistler, lower hybrid, Alfven, and magnetosonic modes, indicating that our model can accurately resolve the physics of waves of interest. The GKe/FKi model is particularly suitable for problems in which the wave modes ranging from Alfven waves to lower-hybrid/whistler waves need to be handled on an equal footing. Figure 1 shows an example of our 1-D benchmark [*Lin et al.*, 2005]. It is found that the GKe/FKi model is identical to the fully kinetic model for $k_\parallel/k_\perp$ smaller than or ~ 0.1, and very close (with 10% error in ω at large $k\rho_e$~1) to the fully kinetic model for $k_\parallel/k_\perp$=0.5. The wave polarizations obtained from the GKe/FKi model also agree with those of the fully kinetic model. This analysis shows indeed that our new kinetic model is very accurate for a system with $\omega<\Omega_e$ and $k_\parallel/k_\perp<1$. For the numerical scheme, we have explored various approaches to implement the above simulation model. The benchmark shows that the numerical results agree very
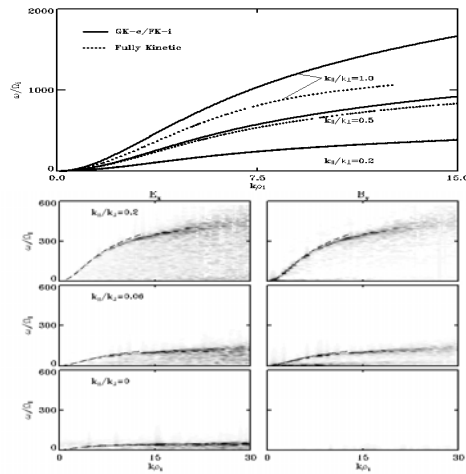

Fig. 1. (a) Analytical linear dispersion relations for whistler wave, obtained from the FK-electron and FK-ion model [Stix, 1992] and the GK-electron and FK-ion model. (b) Comparison between the wave dispersion relations obtained from the numerical scheme and the theoretical analysis based on the GK-electron and the FK-ion model.

well with the theoretical analysis of linear waves. Note that at $k_\perp > \omega_{LH}/V_A$, the electromagnetic mode approaches the quasi-electrostatic lower-hybrid ($k_{//}=0$) and modified two-stream ($k_\parallel \neq 0$) waves. The consistency between the theory and the numerical scheme has been confirmed for cases with various β_e and β_i.

A paper [*Lin et al.*, 2005] has been published in PPCF. A presentation has been given at the Joint Meeting of the 19th International Conference on Numerical Simulation of Plasmas and 7th Asia Pacific Plasma Theory Conference, 2005.

2. Benchmark of GKe/FKi Scheme Against Reconnection Tearing Mode for 2-D Current Sheet

The simulation was then set up for a 2-D current sheet that contains the current sheet normal (B_z) and the anti-parallel magnetic field component (B_x), for benchmark against the kinetic theory of tearing mode. The initial current sheet was assumed to be as in *Wan et al.* [2005] (except a slightly larger sheet thickness) or in the GEM reconnection challenge, with the zero-
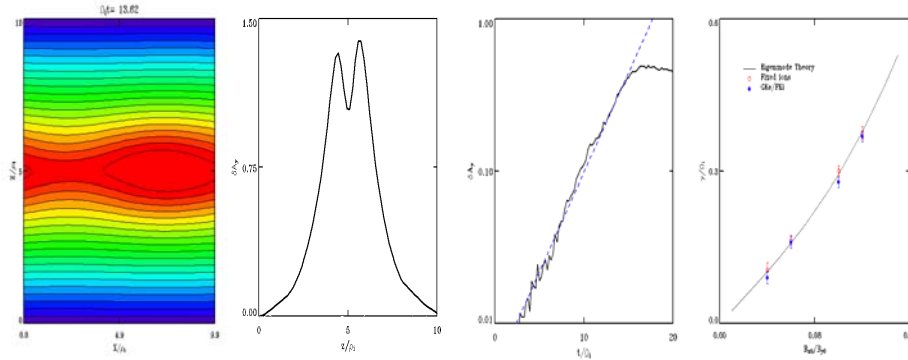

Fig.2. Benchmark of code against the collisionless tearing mode in a 2-D current sheet.

order magnetic field consisting of a large guide field B_G. The left three columns of Figure 2 shows typical field lines (and A_y contours), a typical dominant eigenmode of the simulated tearing instability, and the growth of a dominant tearing mode as a function of time in the GKe/FKi simulation. The right plot shows a comparison between the linear growth rates of the dominant tearing modes, as a function of B_{x0}/B_G, obtained from the kinetic theory and the simulations based on our code. It is seen that our numerical results agree very well with the linear theory. The cases with fixed ions are also consistent with pervious DK-electron simulation of *Wan et al.*

A presentation has been given at the APS-DPP meeting (VP1 133), 2006. Note that this work was limited to a benchmark against existing models. No formal paper was submitted for publication.

3. Simulation of Electrostatic Instabilities in 2-D Harris Sheet and Comparison With Linear Local Theory
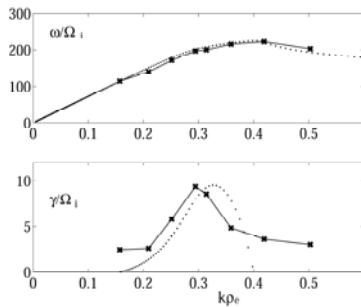

Fig. 3. Comparison of theoretical dispersion relation and the growth rate and simulation result in the linear regime. Thick dotted lines represent analytical result while solid lines represent the simulation result.

In order to benchmark the GKe/FKi scheme and further investigate the current sheet instabilities in the 2-D yz plane that contains the current sheet normal and the guide field B_G (in y), the simulation is carried out using the linearized δf GKe/FKi model in the purely electrostatic limit with the realistic m_i/m_e, and the results are compared with a linear local electrostatic theory. First, the electrostatic stability analysis of a thin current sheet with a small B_G is carried out, and it is shown that the most unstable mode shifts from the lower-hybrid drift type to ion-acoustic type of instability as the strength of B_G increases. Such a mode transition effect has not been reported in the literature. Then, non-local results from the linearized GKe/FKi scheme in the electrostatic limit are compared with the theory under the local approximation. It is shown the comparison of theoretical dispersion relation against the simulated fluctuation frequency and linear growth rate is remarkably good, which implies that the GKe/FKi scheme is a reliable method to study a number of important

problems in contemporary space plasma physics. A comparison between the theoretical and our numerical results are shown in Figure 3 [*Yoon et al.,* 2008].

A paper [*Yoon et al.*, 2008] has been published in Phys. Plasmas. A presentation has been give at the AGU meeting (SM31D-0664), 2007. In addition, we have also collaborated with researcher conducting theoretical analysis of current sheet instabilities, and published a paper on the theoretical analysis [*Zhang et al.*, 2008].

4. Fully Electromagnetic Simulation of Current Sheet Linear Instabilities Under Finite B_G

The instability of Harris current sheet under a broad range of finite guide field (B_G) and with a realistic mass ratio m_i/m_e is studied for the first time. The investigation is conducted using the linearized δf GKe/FKi particle simulation code. The simulation is carried out in the 2-D plane
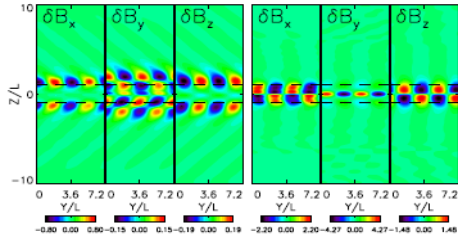

Fig. 4. Linear δf GKe/FKi simulation results: modes A (left, $B_G/B_{x0} =0.1$) and B (right, $B_G/B_{x0} =0.2$) for $k_y\rho_i=6.8$.

containing the guide field along *y* and the current sheet normal along *z*. It is found that for a finite $B_G/B_{x0}\leq1$, where B_{x0} is the asymptotic anti-parallel component of magnetic field, three unstable modes, modes A, B, and C, can be excited in the current sheet. Modes A and C, appearing to be quasi-electrostatic modified two-stream instability (MTSI)/whistler mode, are mainly located on the edge of current sheet. Mode B, on the other hand, is confined in the current sheet center and carries a compressional magnetic field (δB_y) perturbation along the direction of electron drift velocity. Our new finding suggests that mode B may contribute directly to the electron anomalous resistivity in magnetic reconnection. In the cases with extremely large $B_G/B_{x0}>>1$, the wave modes evolve to a globally propagating instability. The simulation shows that the presence of finite B_G modifies the physics of current sheet significantly.

A paper [*Wang et al.*, 2008] has been published in Phys. Plasmas. Two presentations have been give at the APS-DPP meeting (TP8 20), 2007 and the AGU meeting (SM31D-0664), 2007.

5. Modeling Swarthmore Spheromak Reconnection Experiment Using 3-D Hybrid Code

A 3-D hybrid-particle model is developed for investigation of magnetic reconnection in the Swarthmore Spheromak Experiment (SSX). In this numerical model, ions are treated as fully
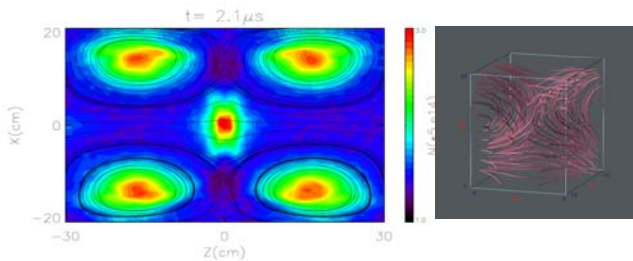

Fig. 5. Field line topologies and ion density contours obtained from our preliminary run [Lin et al., 2008].

kinetic particles, and electrons are treated as a massless fluid. The plasma responds to the electromagnetic fields in a self-consistent manner. The simulation is performed in a cylindrical domain. Initially, a pair of counter-helicity spheromaks are assumed, in which the magnetic field and plasma pressure are set up according to the MHD equilibrium. The ion particles are loaded with a Maxwellian distribution function.

As the simulation proceeds, magnetic reconnection takes place at the current sheet between the pair of the spheromak fields. Plasma is ejected away from the X line toward the central axis, where heating of the transmitted ion is found. Meanwhile, quadrupole out-of-plane magnetic field structure associated with the Hall effects is present around the reconnection site. The preliminary simulation shows consistency with the SSX experiment in several aspects.
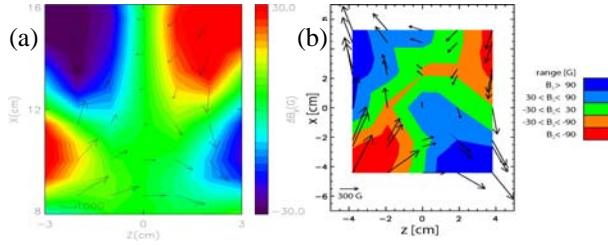
Fig. 6. (a) Change of toroidal field component B_y relative to the initial value in the $y=0$ plane obtained from simulation. The arrows indicate the projected **B** field. (b) B_y measured in an SSX reconnection

Collaboration has been established among researchers in hybrid simulation and SSX reconnection experimentalists. Results of 3D hybrid-particle modeling of SSX reconnection have recently been published in Plasma Physics and Controlled Fusion [*Lin, et al*, 2008].

6. Reversal of Magnetic Field Rotation in the Reconnection Layer Due to Shear Flow Effects

A 1-D resistive MHD simulation of the Riemann problem is carried out for the structure of the outflow region of quasi-steady magnetic reconnection, in the presence of a sheared flow tangential to the initial current (J_y) sheet. Unlike previous studies, the shear flow is in the y direction, perpendicular to the anti-parallel field B_z, with a total change of flow $\Delta V_y \neq 0$ across the current sheet. Cases with symmetric or asymmetric current sheet and various guide magnetic fields B_G are investigated. The simulation shows that in the reconnection layer, the structure of MHD discontinuities change significantly with the strength of the shear flow. The main findings are: (1) In the case initially with a zero guide field ($B_G=0$, for the so-called "anti-parallel reconnection"), the shear flow in V_y produces a finite B_G in the reconnection layer, and two time-dependent intermediate shocks (TDISs) with rotation angle of tangential magnetic field less than 180º. (2) For initial $B_G \neq 0$ (the "component reconnection") the sheared V_y leads to very different magnetic field structures in the two outflow regions on the two sides of the X line. (3) In the cases with the initial $B_G \neq 0$, the existence of the sheared V_y can lead to the reversal of the rotation sense of tangential magnetic field through the reconnection layer. The general simulation results can be applied to space and laboratory plasmas.

A paper [*Sun et al.*, 2006] has been published in J. Geophys. Res.

7. Development and Application of Global Hybrid Simulation Model for Processes Associated With Magnetic Reconnection in the Magnetosphere

A 3-D global hybrid simulation model is developed. Simulations are carried out to study the formation of the dayside low-latitude boundary layer (LLBL) under a purely northward interplanetary magnetic field (IMF). Magnetic reconnection in both northern and southern hemispheres leads to a continued formation of newly closed field lines on the dayside, and a subsequent formation of the LLBL by capture of the magnetosheath ions on the original magnetosheath field lines, as the newly closed field lines shorten. The formation of the LLBL is associated with the tailward spreading of the transmitted ions along the magnetopause as the newly closed flux tubes convect tailward.

In addition, a linkage between energetic ions in the bow shock and the cusp is established using the 3-D self-consistent global hybrid simulation, for a case of the IMF condition favoring high-latitude magnetic reconnection and inter-connection between field lines in the quasi-parallel bow shock and the cusp. A diffuse ion distribution is found in the quasi-parallel shock and foreshock region. Its energy spectrum is well described by an exponential function as in the observed diffuse ions. These bow shock accelerated ions, upon being transmitted into the cusp region, form the bulk of cusp energetic ions.

Two papers [*Lin et al.*, 2006, 2007] have been published in Geophys. Res. Lett.

Publications Related to the Proposed Study

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4. Lin, Y., X. Y. Wang, and S.-W. Chang, Connection Between Bow Shock and Cusp Energetic Ions, Geophys. Res. Lett., **34**, L11107, doi:10.1029/2007GL030038 (2007).
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7. Wang, X. Y., Y. Lin, L. Chen, and Z. Lin, A Particle Simulation of Current Sheet Instabilities Under Finite Guide Field, Phys. Plasmas, **15**, 072103, 2008.
8. Zhang, W., Z. Lin, P. H. Yoon, and X. Y. Wang, Two-fluid Formulation of Lower-Hybrid-Drift Instabilities in Current Sheet Equilibrium With a Guide Field, in press, Comm. Comput. Phys., 2008.