Hybrid Vlasov-Fluid Simulations Of Coherent Phase-Space Structures: Low-Cost Approaches To Studying 2-D Behavior

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The relative advantages and disadvantages to studying the kinetic evolution of highly nonlinear plasma phase-space structures using Vlasov (PDE) vs the more commonly employed PIC methods are well known. A recent example where the low noise of 1-D Vlasov simulations has proven particularly valuable is in the study of current-driven double layers and electron phase-space holes in the return-current region of Earth's auroral ionosphere (R. E. Ergun, et al., *Phys. Rev. Lett.*, **87**, 045003, 2001 [observation]; D. L. Newman et al., *Phys. Rev. Lett.*, **87**, 255001, 2001 [simulation]). There are of course many aspects of the underlying physics that can be addressed only in two or more dimensions. Unfortunately, it is the extension to higher dimensions that has traditionally posed the greatest hurdle to the Vlasov approach because in D physical dimensions phase-space has dimension 2D.

We will present a hierarchy of approaches for the extension of Vlasov simulations to two spatial dimensions—all of which are less computationally demanding that that of a full 5-D phase-space approach. (Phase space is five dimensional in a 2-D magnetized plasma because the two velocity dimensions perpendicular to **B** are coupled via the Lorentz force.) What justifies these *reduced* or *hybrid* models is the fact that the complex phase-space dynamics of double layers and holes can be associated with the *dominant* spatial dimension (z) parallel to **B**, which is also the direction of the driving plasma current. Thus, a full kinetic approach is not necessary in the dimension(s) perpendicular to **B**. Among the approximations already implemented or under development are the following:

1. The simplest extension is to consider both electrons and ions to be highly magnetized with $\Omega_{e,i} \gg \omega_{e,i}$ (generally a good approximation for the electrons but not for the ions in the auroral regions of interest). In this limit, a 2-D plasma can be completely modeled in 3-D (z, v_z, x) phase space because cross-field transport associated with v_x is suppressed by the strong **B**.
2. The next level of complexity is to treat the perpendicular ion dynamics as that of an unmagnetized fluid (with electrons still strongly magnetized). Quasi-Vlasov propagators with phenomenological damping acting on two perpendicular ion velocity modes provide an efficient algorithm in this regime.
3. More realistic finite ion magnetization will be modeled using a "ring" of azimuthal modes at a single fixed magnitude in the perpendicular velocity plane. Linearization of the proposed algorithm yields good agreement with the full kinetic dispersion relation for *pure* ion Bernstein modes in a Maxwellian plasma.
4. An approach to finite electron magnetization using a perpendicular polarization-drift approximation (valid for characteristic frequencies $\omega \ll \Omega_e$) is also under development.

The strengths and limitations of these various models relative to a full Vlasov simulation will be discussed.