Geometrical formulation of hybrid kinetic and gyrokinetic hamiltonian field theory for astrophysical and laboratory plasmas

Felipe Nathan deOliveira-Lopes[1], Daniel Told[1], Karen Pommois[1], Ken Hagiwara[1], Aleksandr Mustonen[1,2], Rainer Grauer[2]

[1]Max Planck Institute for Plasma Physics, Munich, Germany, [2]Ruhr-University Bochum, Bochum, Germany

Higher-order Lie-transform perturbative methods applied to Hamiltonian formulation of guiding-center motion have significant prominence in the field of plasma physics due to their ability to accurately describe the intricate dynamics of particles. The elegant and compact Lagrangian formulation plays a vital role in this process, as it enables the derivation of equations of motion from the Lagrangian two-form, or symplectic two-form.

In this present work, our primary objective is to develop a comprehensive field theoretical hybrid model that incorporates the dynamics of ions within a fully kinetic framework, while simultaneously describing the dynamics of electrons using a gyrokinetic coordinate system transformation. Utilizing the Lagrangian two-form as the starting point, we execute a series of gauge transformations aimed at eliminating the theta dependence up to a predefined ordering. To guarantee theta independence in the Hamiltonian portion of the Lagrangian, a Lie transformation is performed. The dynamics of the system are subsequently derived by employing the variational principle in the action, which also encompasses the electromagnetic fields. This last step give us a complete system, and together with the Vlasov equations for the ions and electrons, can be then solved numerically.

To validate our model as a first approximation, we first conduct a linear analysis and benchmark the solutions of our system against existing literature. Our examination initially focuses on linear electrostatic solutions, taking into consideration Ion Acoustic Waves and Ion Bernstein Waves as examples. Furthermore, we investigate the existence of waves with frequency much higher than ion cyclotron frequency. The lack of such waves in standard gyrokinetic frameworks is a well known barrier to its use in the study of ion frequency range turbulence in space and astrophysical plasma. Subsequently, we compare the linear solutions of our system with those obtained from a fluid and a fully kinetic solver.

In summary, this study serves to introduce a field theoretical hybrid model that can effectively describe the dynamics of ions and electrons in various plasma environments. By validating our model through a linear analysis and benchmarking against existing literature, we aim to provide a valuable tool for investigating kinetic effects in solar wind, laboratory plasma, and potentially, astrophysical plasma.