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Editorial: Adaptive Kinetic-Fluid Models for Plasma Simulations on Modern Computer Systems

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Editorial on the Research Topic

Adaptive Kinetic-Fluid Models for Plasma Simulations on Modern Computer Systems

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Most plasmas are highly non-equilibrium systems, and are characterized by a variety of disparate temporal and spatial scales. They must be described at the kinetic level in term of velocity distribution functions for electrons, ions, and neutral species. Under certain circumstances, simpler hydrodynamic (fluid) descriptions can be applied. Deep understanding of particle kinetics is required for identifying the applicability of fluid description and selecting appropriate closure models, which depend on plasma conditions (collisionless vs. collisional, magnetized vs. non-magnetized), the particle type and energy. The challenges of plasma simulations can be addressed by dedicated multiscale numerical methods such as Implicit-Explicit (ImEx) methods, Asymptotic-Preserving schemes, and hybrid methods [1–3].

This topic is devoted to adaptive kinetic-fluid models for plasma simulations, and contains eight original contributions illustrating the state-of-the-art.

Pfau-Kempf et al. describe Vlasiator—a numerical solver for collisionless magnetized plasma based on direct numerical solution of the Vlasov kinetic equation using Discrete Velocity Models (DVM). The solver is specifically designed for studies of solar wind interactions with near-Earth environment including the bow shock and magnetosheath regions. It is shown that the spatial and velocity resolutions should be adapted together rather than independently for optimal efficiency. This contributes to the ongoing discussion [4–7], of splitting vs non-splitting methods for mesh adaptation in phase space.

Lautenbach and Grauer describe a hierarchical treatment of collisionless magnetized plasmas combining the Vlasov treatment for ions and electrons at the fine level with a 10-moment fluid model at the coarse level for the Geospace Environmental Modeling of magnetic reconnection. We wish to add that new closures for the kinetic-fluid simulations of collisionless plasma have been recently proposed in Hunana et al.[8].

Markidis et al. introduce a Particle-In-Cell framework to cope with the dynamic coupling of kinetic and fluid plasma modeling. The PolyPic method makes use of computational particles for the discretization of both fluid and kinetic equations with the ability for fluid particles to become kinetic when required. This new approach offers promising gains in term of computational efficiency since only a small number of numerical particles is sufficient to represent fluid quantities. This provides an alternative approach to Micro-Macro Particle methods [9, 10].

Dynamically Adaptive Mesh Refinement (AMR) is an important tool to address the nonlinear nature of plasmas and increase accuracy and efficiency of simulations. Fujimoto uses AMR-PIC model for efficient kinetic simulation of magnetic reconnection using dynamically adaptive Cartesian mesh.

The challenges of vastly different time scales due to the disparity of electron and ion mass can be addressed with implicit schemes and coupled algorithms for particle transport and electromagnetics. Ho et al. present adaptive plasma simulations coupling multi-fluid models with a Vlasov-Maxwell and an MHD model. The issues related to the disparate time scales and the collision processes in PIC codes are discussed in Gueroult et al..

Roytershteyn and Delzanno introduce a new spectral method [11] to alleviate the numerical cost of kinetic plasma description together with a parallelization on distributed memory architectures. It relies on an approximation of the distribution function into Fourier modes in the physical space while the velocity space is sampled with Hermite modes. By adjusting the number of Hermite polynomials, it is possible to operate a smooth transition between fluid and kinetic plasma descriptions. The method is shown to be accurate with few Hermite modes in the linear theory, while non-linear plasma turbulence, characteristic of solar winds, is successfully reproduced with a refined sampling of the velocity space.

Another issue emphasizing the multiscale nature of plasma physics is related to plasma quasi-neutrality. The Debye length is routinely very small compared to plasma size and the characteristic time scale of interest is large compared to the reciprocal plasma frequency. It is therefore seducing to embed the quasi-neutrality assumption into plasma simulations, in order to filter out the fast/short scales from the model. Recently, numerical methods have been designed coupling quasi-neutral and non-quasi-neutral plasma models [12, 13]. A different route is explored in Arcese et al. who introduce an innovative method using a patch technique to dissociate the low-frequency plasma equations from the high frequency Maxwell system for electromagnetic fields. This numerical method reveals to be very efficient for simulations of microwave gas breakdown at atmospheric pressure.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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