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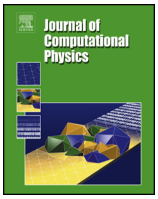

Two-way coupling of a global Hall magnetohydrodynamics model with a local implicit particle-in-cell model

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ABSTRACT

Computational models based on a fluid description of the plasma, such as magnetohydrodynamic (MHD) and extended magnetohydrodynamic (XMHD) codes are highly efficient, but they miss the kinetic effects due to the assumptions of small gyro radius, charge neutrality, and Maxwellian thermal velocity distribution. Kinetic codes can properly take into account the kinetic effects, but they are orders of magnitude more expensive than the fluid codes due to the increased degrees of freedom. If the fluid description is acceptable in a large fraction of the computational domain, it makes sense to confine the kinetic model to the regions where kinetic effects are important. This coupled approach can be much more efficient than a pure kinetic model. The speed up is approximately the volume ratio of the full domain relative to the kinetic regions assuming that the kinetic code uses a uniform grid. This idea has been advocated by [1] but their coupling was limited to one dimension and they employed drastically different grid resolutions in the fluid and kinetic models.

We describe a fully two-dimensional two-way coupling of a Hall MHD model BATS-R-US with an implicit Particle-in-Cell (PIC) model iPIC3D. The coupling can be performed with identical grid resolutions and time steps. We call this coupled computational plasma model MHD-EPIC (MHD with Embedded PIC regions). Our verification tests show that MHD-EPIC works accurately and robustly. We show a two-dimensional magnetosphere simulation as an illustration of the potential future applications of MHD-EPIC.

1. Introduction

Plasma, the most common state of matter in the universe, exhibits incredibly complex dynamics that has been studied for decades, yet our understanding of plasma physics is far from complete. Theoretical analysis is usually limited to relatively simple geometries and the linear regime. Laboratory plasma physics has been developing rapidly, but there are limitations in system size, parameter regime, as well as in the available diagnostics. Space physics and astrophysics provide opportunities for in situ and/or remote observation of large systems dominated by plasmas, including the solar corona, solar wind, magnetospheres, accretion disks, stellar winds, interstellar medium, intergalactic medium, etc., but the observations are inevitably incomplete and we cannot control the observed systems.

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Computational plasma physics allows modeling small as well as large systems with essentially arbitrary parameters including the non-linear regime, and the simulations provide global information about the state of the modeled system. On the other hand, plasma codes use various approximations in the mathematical model, and the discretization errors are often significant due to the limits of available computational resources. The applicability of simulations to real systems, especially in space, are also limited by the lack of complete knowledge of the initial and boundary conditions. Despite these difficulties, there has been tremendous progress in computational plasma physics. Complex engineering designs, for example fusion reactors, plasma propulsion systems, rely heavily on computational models.

Our ability to accurately model plasma phenomena is still severely limited by a major obstacle: the most efficient magnetofluid-type models do not represent many of the kinetic processes, while the kinetic models are too expensive computationally to describe the large scale systems, especially their temporal evolution. One attempt to overcome this challenge is to use hybrid models that combine the fluid description for the electrons with a particle description for the ions. Although hybrid codes offer a viable compromise for some applications, they are still much more expensive than magnetohydrodynamic (MHD) or extended magnetohydrodynamic (XMHD) codes, and they miss the kinetic effects for the electrons that can be essential, for example for modeling magnetic reconnection.

An alternative approach is to couple a kinetic code with an MHD or XMHD code and restrict the kinetic code to a small part of the computational domain. This approach can work well if the kinetic effects are only important (in terms of the parameters of interest) in relatively localized regions, while the fluid description is a good approximation in most of the volume.

In fact, the Space Weather Modeling Framework (SWMF) [2,3] contains coupled kinetic and XMHD codes to model the plasma in the magnetosphere: the inner magnetosphere (defined as the closed field line region with field lines tied to the ionosphere at both ends) is described with a kinetic model, while the global magnetosphere is modeled with an MHD code. In this coupling the kinetic code is a Vlasov-type solver using a bounce-averaged description of the electrons and ions, which is valid as long as the bounce period of the charged particles between the magnetic mirror points is significantly shorter than the dynamic time scales of the system. The velocity distribution is also described with reduced dimensionality with kinetic energy and possibly pitch angle [4–7]. Due to the reduced dimensionality and large time steps, the bounce averaged Vlasov code is about as efficient as a fluid model. In this coupling the MHD code passes the magnetic field solution in the closed field line region and the density and pressure at the open–closed field line boundary to the kinetic code, while the kinetic code returns the density and the pressure (calculated from the distribution function) in the closed field line region to the MHD code so it can “nudge” the solution towards the kinetic solution [8–10]. While this approach has been used quite successfully in the SWMF and resulted in valuable improvement in the predictive capabilities [11], it is only valid in the closed field line region and for slow time evolution.

A more general coupled model that is applicable to arbitrary field geometries and time scales requires a generic kinetic code, such as a Vlasov or a Particle-in-Cell (PIC) solver. There has been some promising research following this idea. The authors of [1] have coupled an explicit particle-in-cell (PIC) code with an ideal MHD code in one dimension, while [12,13] showed a two dimensional (2D) test but the PIC region extended across the full domain in the X dimension, so the coupling was only performed at two boundaries. In these works the coupling algorithm employs an interpolated overlap region between the MHD and PIC codes. In addition, the MHD code uses much coarser grid and much longer time steps than the PIC code, so there is a spatial and temporal averaging of the PIC solution for the coupling.

This paper describes the coupling of an extended MHD code with an embedded implicit Particle-in-Cell code, therefore we name our scheme MHD-EPIC (MagnetoHydroDynamics with Embedded Particle-In-Cell). In particular, we coupled the XMHD code BATS-R-US [14,3] with the implicit PIC code iPIC3D [15]. The new MHD-EPIC model is fully functional in two dimensions (2D) with two-way coupling performed around all four boundaries of the PIC region. The algorithm can and will be easily extended to three dimensions (3D). In all examples shown in this paper the MHD and PIC models have the same spatial and temporal resolution in the vicinity of the PIC region. We can use the adaptive mesh refinement capability of BATS-R-US to coarsen the grid resolution further away from the PIC region. The MHD and PIC regions exchange information directly without an extended overlap layer.

Section 2 describes the basic properties of the XMHD and implicit PIC models. The coupling algorithm employed in MHD-EPIC is described in Section 3. Section 4 shows a number of 2D verification tests and a 2D magnetosphere simulation with an embedded PIC region around the dayside reconnection site. The conclusions and future plans are described in Section 5.

2. Computational models

In this section we describe the particular XMHD and PIC models and the equations solved by them.

2.1. Magnetofluid model

BATS-R-US is a versatile, high-performance magnetofluid code with adaptive mesh refinement (AMR) [14,3]. It can be configured to solve the governing equations of ideal and resistive MHD, semi-relativistic [16], Hall [17], multispecies and multi-fluid [18] extended magnetohydrodynamic equations and most recently XMHD with anisotropic ion pressure [19,20,10]. In addition to the basic equations, there are various source terms that change from application to application: