

Fluid-Accelerated Nonlinear Algorithms for Multiscale Particle-in-Cell Kinetic Simulation of Electromagnetic Collisionless Plasmas

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ABSTRACT

Collisionless plasmas are described by the Vlasov-Maxwell equations. This set of equations is high-dimensional (spanning three spatial and three velocity dimensions), highly nonlinear, and remarkably multi-scale, supporting disparate time and length scales. These features make its efficient numerical integration extremely challenging.

The high-dimensionality of these equations have made particle methods quite attractive. In the plasma context, the method is termed particle-in-cell (PIC). PIC is naturally adaptive in velocity space, and resolves the curse of dimensionality by allowing the estimation of moment integrals be independent of the dimensionality of the underlying phase space. However, PIC can be noisy, and is generally problematic for long-term integrations of the Vlasov-Maxwell equations due to both accuracy limitations (e.g., lack of energy conservation results in secular energy growth which subtracts fidelity from the simulation) and efficiency ones (particle methods are typically explicit, and feature both temporal and spatial stability constraints that force the resolution of both the fastest frequencies and the smallest length-scales supported by the model). These limitations make the long-term, system-scale PIC simulation of physical systems intractable, even with the most powerful supercomputers.

Recently, fully implicit, nonlinear algorithms have been proposed for both electrostatic [1,2] and electromagnetic [3,4] PIC descriptions that enable for the first time truly multiscale kinetic simulations of collisionless plasmas with particle methods. These algorithms 1) feature exact conservation properties, thus avoiding secular growth of conserved quantities, and 2) eliminate the numerical stability constraints of explicit PIC, thus allowing the use of large time steps and mesh sizes (compatible with the physics of interest). The approaches, based on Jacobian-free Newton-Krylov methods, minimize the solver memory footprint by nonlinearly enslaving the kinetic component (particles) to the field equations. Thus, only field equations appear explicitly in the nonlinear residual, resulting in only modest memory requirements for the nonlinear solver. Only a single copy of the particles is needed, as with explicit implementations.

However, despite drastically decreasing the number of degrees of freedom (by allowing larger mesh cells) and the number of time steps required for a given simulation (by allowing large time steps), the resulting algebraic system remains extremely ill-conditioned and requires effective preconditioning for efficiency. A powerful side effect of nonlinear kinetic enslavement is that one can explore moment-based preconditioners. In this talk, we will introduce the fully implicit, conservative multidimensional PIC method, and our approach to fluid preconditioning. We demonstrate the promise of the approach with various challenging numerical examples.

REFERENCES

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