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Nonlinearly implicit, multidimensional, electromagnetic particle-in-cell algorithms for kinetic simulation of plasmas

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Particle-in-cell (PIC) simulation techniques have been widely successful in first-principles simulations of plasma dynamics. However, the fundamental algorithmic underpinnings of standard PIC algorithms have not changed in decades. The classical PIC method employs an explicit approach (e.g. leap-frog) to advance the Vlasov-Maxwell/Poisson system using particles coupled to a grid. Explicit PIC is subject to both temporal stability constraints (either light-wave CFL condition or resolving plasma-wave frequency) and spatial stability (so-called finite-grid instability) constraints, which makes it unsuitable for system-scale kinetic simulations, even with modern super-computers.

Implicit algorithms can potentially eliminate both spatial and temporal stability constraints, thus becoming orders of magnitude more efficient than explicit ones. This has motivated much exploration of these algorithms in the literature since the 1970's. However, the lack of efficient nonlinear solvers for a very large system of particle-field equations required approximations that resulted in intolerable accumulation of numerical errors in long-term simulations.

In this presentation, we discuss a multi-dimensional, nonlinearly implicit electromagnetic PIC algorithm key-1. The approach delivers both accuracy and efficiency for multi-scale plasma kinetic simulations, and extends previous proof-of-principle studies on 1D electrostatic key-2,key-3,key-4,key-5 and electromagnetic systems key-6. To avoid noise issues associated with numerical Cherenkov radiation key-7, we focus our implementation on the Darwin approximation to Maxwell's equations, which eliminates the light wave analytically. The formulation conserves exactly total energy, local charge, ignorable canonical momentum, and preserves the Coulomb gauge. Linear momentum is not exactly conserved, but errors are controlled by an adaptive particle sub-stepping orbit integrator. Key to the performance of the algorithm is a moment-based preconditioner, featuring the correct asymptotic limits. The formulation has been extended to allow mapped meshes, which opens the possibility of accurate body-fitted and/or spatially adaptive PIC simulations. The superior accuracy and efficiency properties of the scheme will be demonstrated with challenging numerical examples.

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